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Exposure and Risk Assessment for Chlorinated Phenols (2-Chlorophenol, 2,4-Dichlorophenol 2,4,6-Trichlorophenol) (Revised)

Little (Arthur D.), Inc., Cambridge, MA

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This report assesses the risk of exposure to 2-chlorophenol, 2-4-dichlorophenol, and 2,4,6-trichlorophenol. This study is part of a program to identify the sources of and evaluate exposure to 129 priority pollutants. The analysis is based on available information from government, industry, and technical publications assembled in June of 1981.

The assessment includes an identification of releases to the environment during production, use, or disposal of the substance. In addition, the fate of chlorophenols in the environment is considered; ambient levels to which various populations of humans and aquatic life are exposed are reported. Exposure levels are estimated and available data on toxicity are presented and interpreted. Information concerning all of these topics is combined in an assessment of the risks of exposure to chlorophenols for various subpopulations.

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AN EXPOSURE AND RISK ASSESSMENT FOR CHLORINATED PHENOLS

2-Chlorophenol
2,4-Dichlorophenol
2,4,6-Trichlorophenol

by

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OFFICE OF WATER REGULATIONS AND STANDARDS
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FOREWORD

Effective regulatory action for toxic chemicals requires an understanding of the human and environmental risks associated with the manufacture, use, and disposal of the chemical. Assessment of risk requires a scientific judgment about the probability of harm to the environment resulting from known or potential environmental concentrations. The risk assessment process integrates health effects data (e.g., carcinogenicity, teratogenicity) with information on exposure. The components of exposure include an evaluation of the sources of the chemical, exposure pathways, ambient levels, and an identification of exposed populations including humans and aquatic life.

This assessment was performed as part of a program to determine the environmental risks associated with current use and disposal patterns for 65 chemicals and classes of chemicals (expanded to 129 "priority pollutants") named in the 1977 Clean Water Act. It includes an assessment of risk for humans and aquatic life and is intended to serve as a technical basis for developing the most appropriate and effective strategy for mitigating these risks.

This document is a contractors' final report. It has been extensively reviewed by the individual contractors and by the EPA at several stages of completion. Each chapter of the draft was reviewed by members of the authoring contractor's senior technical staff (e.g., toxicologists, environmental scientists) who had not previously been directly involved in the work. These individuals were selected by management to be the technical peers of the chapter authors. The chapters were comprehensively checked for uniformity in quality and content by the contractor's editorial team, which also was responsible for the production of the final report. The contractor's senior project management subsequently reviewed the final report in its entirety.

At EPA a senior staff member was responsible for guiding the contractors, reviewing the manuscripts, and soliciting comments, where appropriate, from related programs within EPA (e.g., Office of Toxic Substances, Research and Development, Air Programs, Solid and Hazardous Waste, etc.). A complete draft was summarized by the assigned EPA staff member and reviewed for technical and policy implications with the Office Director (formerly the Deputy Assistant Administrator) of Water Regulations and Standards. Subsequent revisions were included in the final report.

Michael W. Slimak, Chief
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Office of Water Regulations and Standards

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The materials balance for chlorophenols (Chapter 3.0) was adapted from a draft report by Versar, Inc., produced under Contract 68-01-3852 to the Monitoring and Data Support Division, Office of Water Regulations and Standards, U.S. EPA.

1.0. TECHNICAL SUMMARY

1.1 INTRODUCTION

The Monitoring and Data Support Division, Office of Water Regulations and Standards, U.S. Environmental Protection Agency is conducting an ongoing program to identify the sources of and evaluate the exposure to 129 priority pollutants. This report assesses the environmental exposure and risk associated with 2-chlorophenol (2-CP), 2,4-dichlorophenol (2,4-DCP), and 2,4,6-trichlorophenol (2,4,6-TCP). Most environmental releases of these chlorophenols are aquatic discharges from chemical production plants and from the use of derivative products. Chlorophenols are used primarily as intermediates in the synthesis of pesticides, dyes, pigments, and phenolic resins and have only limited direct use.

1.2 RISKS TO HUMANS AND AQUATIC BIOTA

Exposure levels to individuals have been estimated for different exposure conditions. Dose-response extrapolations based on three models have been applied to these exposure levels for 2,4,6-trichlorophenol using data from a study with B6C3F1 mice in which hepatocellular carcinomas and adenomas were induced by ingestion of this compound. Risk estimates of excess individual lifetime tumor incidence associated with 2 4,6-trichlorophenol intakes due to continuous lifetime consumption of drinking water contaminated at average observed levels of 2,4.6-trichlorophenol are in the $<10^{-10}$ to 10^{-7} range. At maximum 2,4,6-TCP concentrations observed in drinking water, estimated excess individual lifetime cancer risk levels range from 10^{-6} to 2×10^{-5}. Estimated excess individual lifetime cancer risk associated with 2,4,6-TCP intakes from ingestion of contaminated fish range from 3×10^{-7} to 1×10^{-5}.

The U.S. EPA Water Quality Criterion for protection of human health specifies criterion levels of 0.12 μg/l, 1.2 μg/l and 12 μg/l 2,4,6-TCP for target risk levels of 10^{-7}, 10^{-6} and 10^{-5}, respectively.

There is considerable controversy over the most appropriate model for performing such extrapolations. Moreover additional uncertainty is introduced into the risk estimates by the choice of a particular set of laboratory data, by the conversion techniques used to estimate human equivalent doses, and by possible differences in susceptibility between humans and rats and mice. Due to the use of a number of conservative assumptions in the risk calculations, the estimated risks most likely over-estimate the actual risk to humans.

A quantitative estimation of the risks to humans associated with exposure to 2-chlorophenol or 2,4-dichlorophenol could not be adequately made due to the lack of available toxicological data on these compounds, particularly with respect to long-term effects. However, margins of safety (lowest effects level divided by exposure level) were estimated for these two compounds. These calculations provide a rough indication of the relative safety of typical exposure situations. Margins of safety for 2-chlorophenol were estimated to be 2 x 10^4 for maximum exposure for fish-eaters, and 2 x 10^5 for a more typical exposure for fish-eaters, and 1 x 10^7 for ingestion of drinking water alone. For 2,4-dichlorophenol, the margins of safety are estimated to be 2 x 10^4 for the maximum exposure (including ingestion of food and drinking water) and 2 x 10^7 for a more typical exposure through drinking water only. It must be emphasized that these margins are based on very limited short-term effects data and limited exposure data. Chronic data for 2-CP and 2,4-DCP, which are not available at this time, would likely result in the determination of lower effects levels which would be reflected in a decreased margin of safety.

The risk of adverse environmental exposure of aquatic communities to chlorophenols appears to be low. Assuming 10 μg/l as a typical mean concentration for any of the chlorophenols in U.S. surface waters (probably an overestimate), the lowest chronic effects level exceeds this concentration by over one order of magnitude while acute LC_{50}'s exceed it by over two orders of magnitude. There is a possibility, due to the limited number of species which have been tested, that more sensitive species do exist but have not been identified at this time.

1.3 HUMAN EXPOSURE AND EFFECTS

Daily exposure to chlorophenols in drinking water was estimated to be 0.4 μg/day as an average level and 100 μg/day as a maximum. These estimates are based on concentrations reported for 2,4-dichlorophenol in drinking water; no equivalent data were available for other chlorophenols. The frequency of occurrence of high chlorophenol concentrations in water is unknown.

Sources of chlorophenols to surface and drinking water include direct industrial wastewater discharges from organic chemicals, pesticide manufacturers, and plastics producers, timber and pulp/paper plants, and foundries. Chlorination of phenols during industrial, POTW, and drinking water treatment processes is a potential source of chlorophenols. Another source is from the degradation of complex chlorinated organics (i.e., the herbicide 2,4-D or pentachlorophenol) into lower chlorinated phenols.

Ingestion of contaminated food results in the highest known exposure levels of chlorophenols for humans. Maximum exposure through consumption of fish was estimated to be 137 μg/day for 2-chlorophenol, 26 μg/day for 2,4-dichlorophenol, and 95 μg/day for 2,4,6-trichlorophenol. These numbers are based on theoretical bioconcentration factors assuming fish are exposed to concentrations of 30-50 μg/l (highest ambient water concentrations reported in STORET), which may result in an overestimation. Due to a paucity of monitoring data, it is not possible to determine how common an occurrence fish contamination by chlorophenols is. Human consumption of contaminated kidney from cattle fed 2,4-D-treated fodder has an associated maximum exposure of 280 μg/day of 2,4-dichlorophenol. There is a potential for contamination of edible crops with chlorophenols present as impurities or breakdown products in agricultural herbicides, but no reported measurements of residue levels were available.

Limited data are available concerning the effects of chlorophenols on humans or laboratory animals. In general, the compounds appear to be readily metabolized and excreted in urine. Acute median lethal doses range from 100 to 900 mg/kg for 2-chlorophenol and 2,4,6-trichlorophenol, and from 400 to 4,000 mg/kg for 2,4-dichlorophenol. No chronic studies were available on 2-chlorophenol to estimate the effects of long-term human exposure to low concentrations. An acceptable daily intake level of 7 mg 2,4-dichlorophenol/day has been estimated for humans, based on a long-term feeding study in rats. The compound 2,4,6-trichlorophenol was determined by NCI to be carcinogenic in both rats and mice, indicated by increased incidences of leukemia and hepatocellular carcinoma in rats and mice, respectively, at concentrations on the order of 5,000 mg/kg diet. Based on limited studies, the other two chlorophenols do not appear to be carcinogenic.

1.4 AQUATIC BIOTA EXPOSURE AND EFFECTS

The small monitoring data base for chlorophenol concentrations in surface water limits the assessment of environmental exposure of aquatic organisms. Concentrations for all three compounds were usually reported at less than 10 µg/1 and at a maximum of 100 µg/1 according to the STORET data base (1977-1979). Most of the observations were remarked as equal to or below the level of detection so the data base overestimates ambient environmental concentrations.

Higher concentrations than those reported in STORET are likely to be associated with certain industries using or producing chlorophenols; however, the limited data can provide only examples of the levels to which aquatic organisms may be exposed. Higher than ambient concentrations may be found in the vicinity of chemical producers, pesticide manufacturers, pulp and paper mills, wood processers, textile manufacturers, leather tanners, and sewage treatment plants. The compound 2-chlorophenol tends to be nondetectable or detected at lower concentrations than the other two chlorophenols. Effluent concentrations on the order of 1 to 100 mg/1 have been reported for various industries; however, on dilution in the receiving waters, these concentrations are expected to be considerably reduced by factors such as biodegradation, volatilization and adsorption.

Fish kills attributed to chlorophenols in general (possibly including pentachlorophenol) were reported following discharge from cooling towers and wood preservative storage tanks. The leakage of 2,4-dichlorophenol from a break in a holding dike was specifically responsible for another large fish kill.

The limited information on the effects of chlorophenols on aquatic organisms indicates acute toxicity for fish at concentrations on the order of 0.1-10 mg/1. Reported LC_{50}'s for bluegill were 6.6, 2.02, and 0.32 mg/1, respectively, for 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6 trichlorophenol. Daphnia were affected at concentrations ranging from 2 to 11 mg/l. Chronic values for fathead minnows were reported >3.9 mg/l, 0.37 mg/l, and 0.72 mg/l for 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol, respectively. Toxicity tended to increase with the degree of chlorination. Water hardness, the only variable tested for its effect on chlorophenol toxicity, had no influence on the toxicity of 2-chlorophenol.

1.5 ENVIRONMENTAL FATE

The majority of chlorophenols entering the environment is discharged to water primarily by chemical producers. Following release, adsorption, volatilization, and biodegradation are expected to be the major processes responsible for removal of chlorophenols from the water column. Adsorption onto organic matter appears to be more significant than adsorption onto clay material, and, based on their octanol/water partition coefficients, trichlorophenol is more likely to be sorbed than the lower chlorinated phenols. Volatilization to the atmosphere of the soluble fraction of chlorophenols is likely based on the compounds' high vapor pressures, especially the mono- and dichlorophenols. No actual measurements of volatilization from water were available to confirm its significance as a transport process for chlorophenols. Biodegradation is an important transformation process, especially for the lower chlorophenols. Acclimated microbial cultures can reduce mono- and dichlorophenol concentrations to negligible levels in about one week under laboratory conditions. Aquatic species may bioaccumuluate all three chlorophenols to levels 100 to 400 times above concentrations in water.

Dichlorophenol is released to soil through the application of the herbicide 2,4-D and an unknown amount of all the chlorophenols enter the soils as impurities or breakdown products of 2,4-D, 2,4,5-T, silvex, and other pesticides. The movement of chlorophenols is controlled by adsorption onto organic matter and, apparently less importantly, sorption onto bentonite and other clays. The sorption bond is hypothesized to be weak and lower chlorophenols are easily desorbed by water based on similar observations on acidic pesticides. As in water, biodegradation is an important removal process for chlorophenol in soil. Soil populations can significantly reduce chlorophenol concentrations in about two to three weeks and in even less time following acclimation. In porous soils and conditions unfavorable to biodegradation, there is a potential for migration of chlorophenols into groundwater. In agricultural areas, runoff and sediment transport are likely to transfer chlorophenols from soil to surface water, especially immediately after their application to land.

Very little is known about the atmospheric fate of chlorophenols following emission. However, the total amount of chlorophenols released to air each year is small compared to other better characterized environmental compartments. There were no monitoring data available for any of the chlorophenols to indicate their presence in ambient air. Based on their physical and chemical properties, the chlorophenols are estimated to have an atmospheric half-life of roughly three weeks controlled by free radical oxidation. This estimate, however, has not been validated in the laboratory or under field conditions. Little is known about other atmospheric fate processes.

Secondary treatment is very effective at removing chlorophenols from wastewater, especially if well acclimated microbial populations are present. Inhibitory levels in activated sludge for 2,4-dichlorophenol and 2,4,6-trichlorophenol have been reported at 200 mg/l. Other commonly employed treatment techniques, such as those used in primary treatment, do not appear to be very effective at chlorophenol removal.

Monitoring data on chlorophenol concentrations in environmental media are very few and limited to surface water. According to the STORET data base, the total of 300 ambient samples for chlorophenols were all at or below the detection limit (usually 10 μg/l, occasionally 100 μg/l). Concentrations in an effluent from a chemical plant ranged from 3 mg/l to 73 mg/l for the three chlorophenols. No measurements of chlorophenols in air or soil were available.

1.6 MATERIALS BALANCE

The majority (85%) of the known (600 kkg) environmental releases of the three chlorophenols are to surface water. Releases to air and through generation of solid waste are expected to be negligible. A small amount of 2,4-dichlorophenol is released to land in the use of the herbicide 2,4-D, and some of this may eventually enter water through agricultural runoff.

Over 90% of the known discharges of chlorophenols to water are made during the production of 2-chlorophenol and 2,4-dichlorophenol; releases associated with production of 2,4,6-trichlorophenol are unknown. Monitoring data of chlorophenol concentrations in various industrial effluents indicate that 37% of the positive samples were found in organic chemical and plastics producers. Chlorophenols are also reported in effluents from timber and pesticide-related industries and from foundries. The occurrence in foundry effluents is, at this point, unexplained.

2.0. INTRODUCTION

The Monitoring and Data Support Division, Office of Water Regulations and Standards, U.S. Environmental Protection Agency is conducting a program to evaluate the exposure to and risk of 129 priority pollutants in the nation's environment. The risks to be evaluated include potential harm to human beings and deleterious effects on fish and other biota. The goal of the tasks under which this report has been prepared is to integrate information on cultural and environmental flows of specific priority pollutants and estimate the risk based on receptor exposure to these substances. The results are intended to serve as a basis for developing suitable regulatory strategy for reducing the risk, if such action is indicated.

This report is intended to provide a brief, but comprehensive summary of the manufacture, use, distribution, fate, effects, and potential exposure and risk in regard to 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol. In order to make effective use of this report and to understand the uncertainties and qualifications of the data presented herein, several problems must be identified.

The three chlorophenols are produced primarily for use as intermediates in the manufacture of other chlorinated phenols and many organic chemicals. The compound 2,4,6-trichlorophenol is used directly to a lesser degree as a disinfectant in assorted products. The production and use emissions data for all chlorophenols are very limited.

A source of chlorophenols to waterways which is of unknown but potentially high significance is inadvertent synthesis during chlorination of phenols or lower chlorinated phenols. Production may occur in POTWs, drinking water treatment, and in certain industrial treatments. These sources should be accounted for as best as possible in a materials balance; however, in this case it was not possible to quantify these releases.

Environmental fate and monitoring data regarding the chlorophenols are few. It is difficult, therefore, to predict and confirm their persistence in the environment. In order to estimate the chlorophenols' environmental behavior, extrapolations from similar substances (such as derivative products) and based on the compounds' physical and chemical properties were made. The estimates of exposure to chlorophenols are associated with some uncertainty due to these inadequacies.

This report is organized as follows:

- Chapter 3.0 contains information on the production, consumption, discharge, and disposal of chlorophenols.

- Chapter 4.0 describes the environmental fate of chlorophenols in four pathways originating from the point of release and presents available monitoring data on levels in environmental media.
- Chapter 5.0 presents reported effect levels in humans and laboratory animals and exposure pathways for humans.
- Chapter 6.0 discusses reported effects levels and exposure pathways for aquatic organisms.
- Chapter 7.0 discusses risk of exposure to chlorophenols for the general population of humans and aquatic organisms.
- Appendix A provides details concerning the production and emission estimates in Chapter 3.0.

3.0 MATERIALS BALANCE

3.1 INTRODUCTION

In this chapter, data on the sources of chlorophenols and their pathways of entry into the environment are presented. A materials balance checklist was used to help locate the potential sources of the compounds. Current and past EPA reports, other readily available literature and personal contacts with EPA provided the basis for this chapter, which was prepared by Versar, Inc.

Appendix A presents the methodology employed to derive estimates of production, use, and emissions. The environmental compartments (air, land, water, etc.) initially receiving and transmitting the compounds are identified in this chapter whenever possible, as are the locations at which the environmental loadings occur. There are many uncertainties in this analysis; current releases have not been identified from all sources, past releases are not well documented, and future releases are difficult to predict. Nevertheless, sufficient information is available to indicate in general terms the nature, magnitude, location, and time dependence of pollutant loading of the environment with chlorophenols.

3.2 MATERIALS BALANCE

This section presents a materials balance for three chlorophenols: 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol for the year 1977. A total of 22,000 to 38,000 kkg of all compounds were produced in 1977. There were no reported imports or exports of any of the chlorophenols. Because of the lack of information specific to the chlorophenols, production quantities, use statistics, and emissions have been estimated based on data for related compounds: pentachlorophenol, phenol, and 2,4-dichlorophenoxyacetic acid.

The majority of the supply of these compounds is used to produce salts, esters, or other chlorophenol derivatives. These derivatives are used as herbicides, insecticides, germicides, or in related applications. Small quantities of chlorophenols may have a highly specialized use, but the extent of their use in these applications is unknown. The most significant known source of environmental emissions of these compounds is the discharge from production operations or from derivatives in the biosphere. Total known environmental emissions for all 3 chlorophenols are estimated to be about 600 kkg, with the majority released to aquatic systems. Solid wastes and discharge to POTWs are believed to be negligible. Summaries of production, use, and emissions are presented in Table 3-1 and Figure 3-1. An estimated 1 to 70 kkg of 2,4-dichlorophenol is released to land each year as a contaminant in 2,4-D herbicide applications.

3.3 PRODUCTION

There are thirteen isomers of chlorophenols which are produced in the United States. Recent production data on all but one of these

TABLE 3-1. SUPPLY, CONSUMPTION, AND EMISSIONS OF THREE CHLOROPHENOLS (1977)[a]

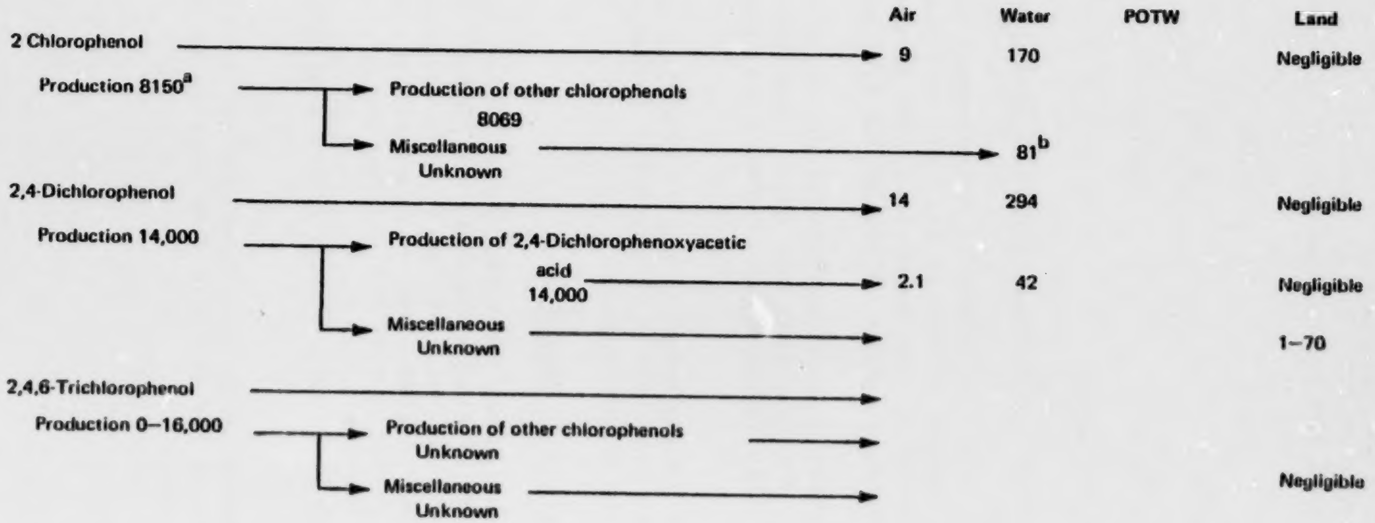
	Supply (kkg)	Consumption (kkg)	Airborne Emissions (kkg)	Aquatic Discharge (kkg)	Discharge to POTW (kkg)	Discharge to Land (kkg)
PRODUCTION AND EMISSIONS						
2-chlorophenol	8,150	b	9	170		Negligible
2,4-dichlorophenol	14,000		14	294		Negligible
2,4,6-trichlorophenol	0-16,000					
USES AND EMISSIONS						
2-chlorophenol						
Production of other chlorophenols		8,060		81[c]		Negligible
Miscellaneous		81				
2,4-dichlorophenol						
Production of 2,4-dichlorophenoxyacetic acid	14,000		2.1	42		Negligible
Miscellaneous						1-70
2,4,6-trichlorophenol						
Insecticide and related products						
Production of higher chlorophenols						
TOTAL	22,150- 38,150	22,150 +	25.1	587		70

[a] Date is based on material presented in Appendix A.

[b] Blanks denote information not available.

[c] Receiving medium either surface water or POTWs.

Source: Versar Inc., estimates.


Air
Water
POTW
Land
2 Chlorophenol
9
170
Negligible
Production 8150a
Production of other chlorophenols
8069
Miscellaneous
Unknown
81b
2,4-Dichlorophenol
14
294
Negligible
Production 14,000
Production of 2,4-Dichlorophenoxyacetic
acid
14,000
2.1
42
Negligible
Miscellaneous
Unknown
1–70
2,4,6-Trichlorophenol
Production 0–16,000
Production of other chlorophenols
Unknown
Miscellaneous
Unknown
Negligible

Emissions from storage and transportation, if any, are unknown.

a. All units in metric tons.
b. Receiving medium either surface water or POTWs.

Source: Versar, Inc., estimates.

FIGURE 3–1 COMMERCIAL FLOW OF THREE CHLOROPHENOLS – 1977

compounds is proprietary and unpublished. The production of the three isomers addressed in this report, 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol has been estimated for 1977 as follows:

Compound	kkg
2-chlorophenol	8,157
2,4-dichlorophenol	14,000
2,4,6-trichlorophenol	0-16,049

The basis for these estimates is presented in Appendix A.

The production of these compounds is interrelated because they have little commercial importance separately and thus only small amounts of these compounds are isolated. The balance is used directly in mixed batches for the production of other chlorophenols (JRB Associates 1980).

A total of four chemical plants produced the three chlorophenols in 1977. The names of the producers and their locations are listed in Table 3-2 as well as other plants which produce other isomers of the same compounds.

Chlorophenols are manufactured by two processes using different feedstock. One process uses phenol as precursor feedstock, and the other uses the analogous chlorobenzene.

3.3.1 Direct Chlorination of Phenol

A flowsheet for the direct chlorination of phenol is presented in Figure 3-2. Phenol, chlorine, and catalyst are charged to a reactor and the product is separated and purified by crystallization. The temperature and stoichiometric quantities of reactants are controlled in order to optimize the production of the desired isomer, but a mixture of isomers invariably results. The chemistry of phenol, discussed in Appendix A, dictates which isomers result from the direct chlorination of phenol.

Because of the strong ortho-para directing of the hydroxyl group, successive substitution on the aromatic ring results in the following isomers by ring nomenclature:

TABLE 3-2. U.S. PRODUCERS OF CHLOROPHENOLS (1977)

Company	Location	Monochlorophenol			Dichlorophenol						Trichlorophenol	
		Ortho	Para	Meta	2,3	2,4	2,5	2,6	3,4	3,5	2,4,6	2,4,5
Dow Chemical Co.	Midland, MI	x	x			x					x	x[a]
Monsanto Company	Sauget, IL	x	x			x						
Aldrich Chemical Co.,Inc.	Milwaukee, WI			x				x	x	x		
Eastman Kodak Co.	Rochester, NY			x								
Reichold Chemicals, Inc.	Tacoma, WA											
Vulcan Materials Co.	Wichita, KS											
Transvaal, Inc.	Jacksonville FL					x						x
R. S. A. Corp.	Irwindale, CA				x			x		x		
Rhodia, Inc.	Freeport, TX					x						
Northwest Industries, Inc.	Beaumont, TX						x					

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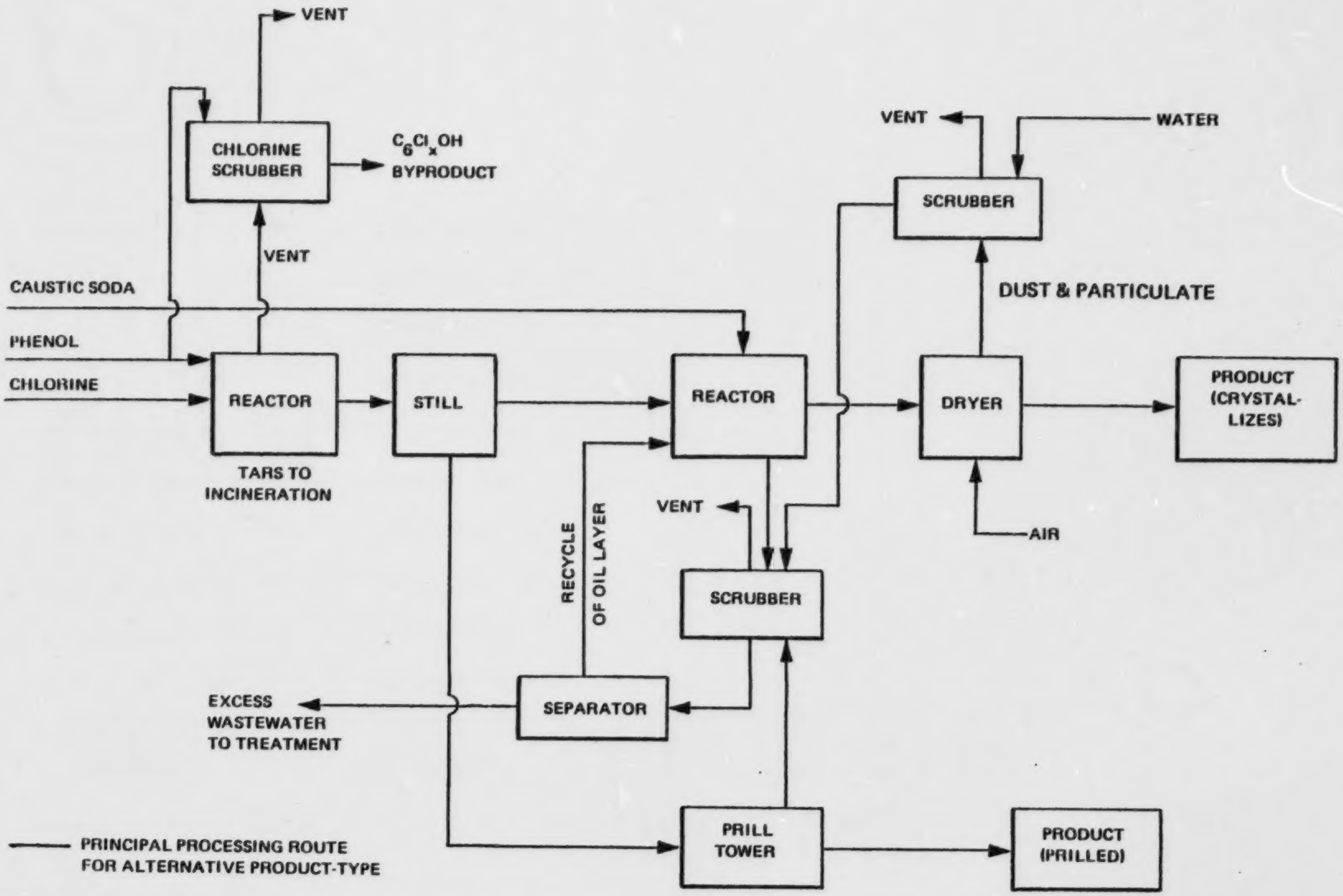
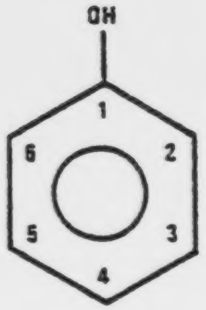
[a] Marketed as Dowicide® 2

Source: SRI (1978).


VENT
CHLORINE SCRUBBER
C_6Cl_xOH BYPRODUCT
VENT
CAUSTIC SODA
PHENOL
CHLORINE
REACTOR
TARS TO INCINERATION
STILL
REACTOR
RECYCLE OF OIL LAYER
VENT
SCRUBBER
SEPARATOR
EXCESS WASTEWATER TO TREATMENT
PRILL TOWER
PRODUCT (PRILLED)
VENT
WATER
SCRUBBER
DUST & PARTICULATE
DRYER
AIR
PRODUCT (CRYSTALLIZES)
PRINCIPAL PROCESSING ROUTE FOR ALTERNATIVE PRODUCT-TYPE

Source: Tracor-Jitco (1978a).

FIGURE 3–2 GENERAL PROCESS FLOW DIAGRAM FOR CHLOROPHENOL PRODUCTION VIA DIRECT CHLORINATION



PHENOL

Phenol nomenclature:
Ortho substitution - positions 2 or 6
Para substitution - position 4
Meta substitution - positions 3 or 5

Isomers Produced by Direct Chlorination

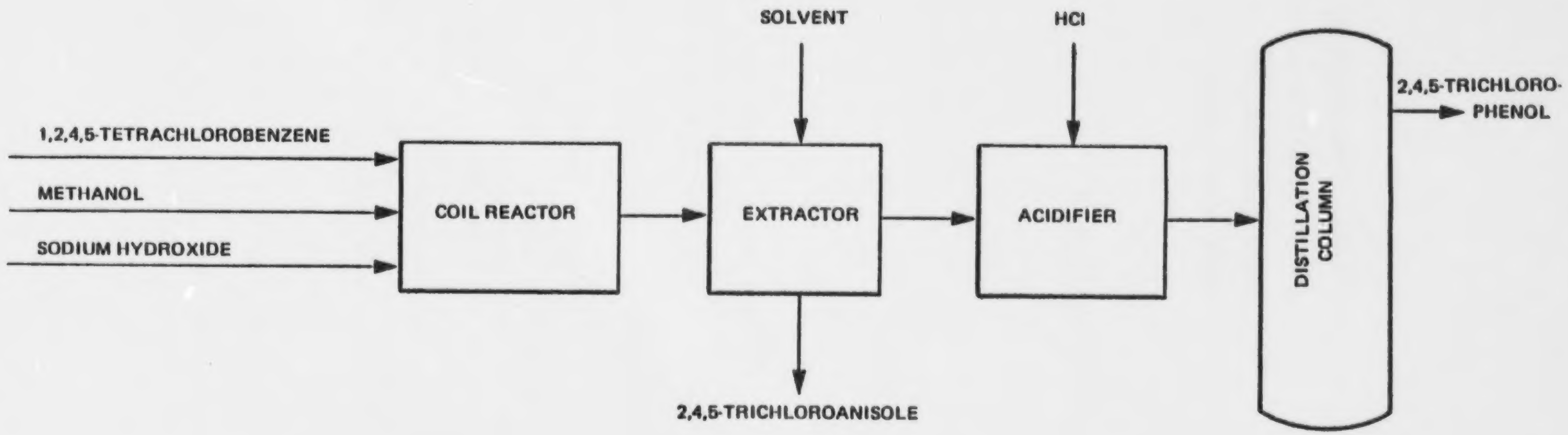
2 chlorophenol
4 chlorophenol
2,4-dichlorophenol
2,6-dichlorophenol
2,4,6-trichlorophenol
2,3,4,6-tetrachlorophenol
Pentachlorophenol

Most of the above products are manufactured via the chlorination of phenol, although small amounts of the ortho and para monochlorophenol are produced by the hydrolysis of the appropriate dichlorobenzene.

3.3.2 Hydrolysis of Chlorobenzenes

The hydrolysis of chlorobenzene is carried out in aqueous alkali solutions at high temperatures and pressure. This reaction is feedstock specific with the substitution of a hydroxyl group for a chlorine on the aromatic ring. A generalized flow diagram for this process is presented in Figure 3-3. Although the process can be used to manufacture the isomers discussed in Section 3.3.1, it is not recommended because of the formation of chlorinated dibenzo-p-dioxins which detracts from the reaction yield. The hydrolysis route is used to produce the following isomers using the appropriate chlorobenzene:

3-chlorophenol
2,3-dichlorophenol
2,5-dichlorophenol
3,4-dichlorophenol
3,5-dichlorophenol
2,4,5-trichlorophenol


SOLVENT
HCl
1,2,4,5-TETRACHLOROBENZENE
METHANOL
SODIUM HYDROXIDE
COIL REACTOR
EXTRACTOR
ACIDIFIER
DISTILLATION COLUMN
2,4,5-TRICHLOROPHENOL
2,4,5-TRICHLOROANISOLE

Source: Tracor-Jitco (1978b).

FIGURE 3–3 PRODUCTION SCHEMATIC FOR 2,4,5-TRICHLOROPHENOL PRODUCTION BY HYDROLYSIS OF 1,2,4,5-TETRACHLOROBENZENE

3.3.3 Emissions From Production

The emissions of chlorophenols summarized in Table 3-1 were extracted or based on data from a JRB Associates (1980) materials balance for chlorophenol. These estimates are uncertain and should be used with caution. Production sources of airborne emissions include the reactor vent, the dryer vent, and distillation vents. Aquatic discharges may occur from spills of scrubber liquors or from purification steps. Reportedly, solid wastes from column and reactor tars are negligible. The total identified annual airborne emissions are estimated at 23 kkg. The total identified annual aquatic discharges from the production process are estimated at 464 kkg. Appendix A presents the assumptions and calculations for these estimates.

3.3.4 Emissions from Transport and Storage

There is no information available to estimate emissions from the transport and storage of chlorophenols. Only a small fraction of the total amount produced of any of these compounds is isolated for direct use; the majority is used within the plant where it was produced in the production of chlorophenol derivatives. Consequently, chlorophenol emissions due to transportation or storage at these sources are believed to be minimal.

3.3.5 Miscellaneous Emissions

Sources of chlorophenols to the environment other than from direct industrial releases have been reported. Chlorophenols are apparently intermediate products resulting from the biodegradation of chlorinated benzenes and certain pesticides (Ballschmitter et al. 1977, Engst et al. 1977). This subject is discussed in greater detail in Chapter 4.0.

Chlorophenols may also be produced in POTWs, drinking water, and through industrial wastewater treatment due to chlorination (JRB Associates 1980). Phenol is one of the most reactive aromatic compounds under conditions of dilute aqueous chlorination (Aly 1968, Barnhart and Campbell 1972, Carlson and Caple 1976; Carlson et al. 1975). The most commonly formed products of phenol chlorination are thought to be ortho- and para-chlorophenol, 2,4- and 2,6-dichlorophenol, and 2,4,6-trichlorophenol (MCA 1972). In our study, the synthesis of 2-chlorophenol resulted from the reaction of 10 mg/l phenol and 20 mg/l chlorine, concentrations which are likely to be encountered in treatment processes (Barnhart and Campbell 1972). Monochlorophenols were detected in lakes receiving a chlorinated effluent from a coal-fired electric plant (Jolley et al. 1978). In another laboratory chlorination experiment (Burttschell et al. 1959), reaction of 20 mg phenol/ml with 40 mg/l chlorine resulted in a mixture of 1-2% phenol, 2-5% 2-chlorophenol, 20% 2,4-dichlorophenol, 40-50% 2,4,6-trichlorophenol, and other chlorinated phenol isomers. Trichlorophenols, but no dichlorophenols, were detected in municipal wastewaters which were superchlorinated during treatment (Glaze et al. 1978).

Even with such strong evidence supporting the generation of chlorophenols during water treatment processes, it was not possible to estimate the annual contribution of this indirect source to the environmental loading of chlorophenols. Most of the data available are laboratory-derived and theoretical. Comparison of influent and effluent levels of chlorophenols in POTWs in the limited field data available do not indicate synthesis of chlorophenols during treatment (Versar, Inc..1977, Scow et al. 1981). More monitoring is required before any conclusions can be drawn about the actual environmental significance of chlorophenol synthesis during wastewater treatment.

There are no known natural sources of chlorophenols. Due to the rarity of naturally occurring chlorine-containing compounds, chlorophenols are expected to be anthropogenic in origin.

3.3.6 Emissions From POTWs

A potential source of chlorophenols to surface water is from POTWs. In a monitoring study of 20 U.S. POTWs (Feiler 1980), the three chlorophenols were detected in 5% of the samples of influent concentrations (152 samples) and in less than 5% of the effluent (129 samples) and sludge (203 samples) concentrations. Therefore, since the limited data available indicated a low frequency of detectable chlorophenol concentrations in POTWs, no national loading rate of chlorophenols from POTWs to surface water was estimated.

3.4 USES

A relatively small amount of any of the chlorinated phenols have direct uses. The major application of these compounds is as intermediates in preparation of other chlorinated organic compounds. Table 3-3 lists the major and minor uses of each of the chlorophenols.

Most of the 2-chlorophenol produced is used as feedstock for the production of higher chlorophenols with only about 1% (≃81 kkg) isolated for uses other than as an intermediate in the production of other phenols (JRB Associates 1980). Other uses are in the production of specialized phenolic resins, as a specialty solvent in the rubber industry, as a polymer intermediate in the manufacture of fire-retardant varnishes, and as an aminizing agent for cotton fabric (Kozak et al. 1979).

The major use of 2-4-dichlorophenol is in the manufacture of 2,4-dichlorophenoxyacetic acid (2,4-D), which is subsequently processed into various salts and esters. These salts and esters are used in conjunction with other compounds in the formulation of fungicides, herbicides, molluscicides, and other related compounds (SRI 1978, U.S. EPA 1973). A list of the eleven 2,4-DCP producers (as of 1977) is presented in Table 3-4. Other pesticides produced from 2,4-DCP are sesone and nitrofen (Kozak et al. 1979).

TABLE 3-3. USES OF 2-CHLOROPHENOL, 2,4-DICHLOROPHENOL, AND 2,4,6-TRICHLOROPHENOL

Compound	Use
2-Chlorophenol	Feedstock for production of: a) higher chlorinated phenols used as fungicides, slimicides, bacteriacides, antiseptics, deodorants, wood and glue preservatives. b) phenolic resins In sulfur- and nitrogen-extracting processes from coal.
2,4-Dichlorophenol	Feedstock for production of: a) 2,4-dichlorophenoxyacetic acid (2,4-D) b) 2,4-D derivatives used as germicides, soil sterilants, and in other applications c) various methyl compounds used as antiseptics, as seed disinfectants, and in moth-proofing d) pentachlorophenol e) miticides (by reacting with benzene sulfonyl chloride)
2,4,6-Trichlorophenol	Used directly as germicide, as bacteriacide, as glue and wood preservative, and in anti-mildew treatment. Feedstock for production of: a) 2,3,4,6-tetrachlorophenol used as a germicide, as a bacteriacide, as a glue and wood preservative, and anti-mildew treatment. b) pentachlorophenol.

Source: U.S. EPA (1980a), U.S. EPA (1980b), U.S. EPA (1980c).

TABLE 3-4. MANUFACTURERS OF 2,4-DICHLOROPHENOXYACETIC ACID AND ITS ESTERS AND SALTS

Company	Location
Dow Chemical Co., U.S.A.	Midland, MI
Imperial, Inc.	Shenandoah, IA
North American Philips Corp. Thompson-Hayward Chem. Co., Subsidiary	Kansas City, KS
PBI-Gordon Corp.	Kansas City, KS
Rhodia Inc. Agricultural Division	Portland, OR St. Joseph, MO
Riverdale Chem. Co.	Chicago Heights, IL
Rorer-Amchem Amchem Products, Inc. Division	Ambler, PA Fremont, CA St. Joseph, MO
Vertac, Inc. Transvaal, Inc., subsidiary	Jacksonville, AR

Source: Versar, Inc. (1980).

The compound 2,4-DCP is present as an impurity in 2,4-D at concentrations ranging from 70 to 4,500 mg/kg (Aly and Faust 1964). An estimated 16 x 10^3 kkg of 2,4-D were used for agricultural purposes in 1971 (USDA 1974). Therefore, in 1971, approximately 1 to 70 kkg of 2,4-DCP was applied to soil in conjunction with 2,4-D application.

The compound 2,4-6 trichlorophenol has numerous potential uses, but the majority produced is used as feedstock for the manufacture of higher chlorophenols. The amount used directly is unknown. Trichlorophenol and its derivatives may be used as a wood preservative, glue preservative, ingredient in insecticide and bactericide, and as an anti-mildew treatment for textiles (JRB Associates 1980, U.S. EPA 1975).

Small quantities of all three of the compounds may have other highly specialized unknown uses.

3.4.1 Emissions From Uses

Relatively minor amounts of these compounds have direct end-use applications such as pesticide use, and these derivatives are known to degrade in the environment (JRB Associates 1980). Assessing environmental emissions of these compounds based on their production and use is virtually impossible since their production is only estimated and their use pattern, in terms of quantities, is poorly defined.

However, limited sampling data indicate that two of these compounds (2,4-DCP and 2,4,6 TCP) have been detected in effluents from other types of industrial operations (U.S. EPA 1980d). In most cases the estimated annual discharge is less than 1 kkg at each plant. A summary of these industries and the estimated discharge is presented in Table 3-5. For other than pesticide manufacturers, the presence of the chlorophenol compounds is presumably due to their use by these industries in anti-mildew treatment, wood preserving, disinfection, and bacteriacidal treatment.

3.5 FUTURE PROJECTIONS

Trends in the production of the three chlorophenols addressed in this report are not readily discernible bacause actual production values are not reported. Since the major use of these compounds is in the production of higher chlorophenols, there may be a correlation between the production of these compounds and the production of pentachlorophenol. Pentachlorophenol production from 1960 to 1981 is presented in Table 3-6; production is expected to exhibit a 4% annual growth in the next few years.

TABLE 3-5. ESTIMATED DISCHARGES OF 2,4-DICHLOROPHENOL AND 2,4,6-TRICHLOROPHENOL FROM SELECTED INDUSTRIES

Industry[a]	Number of Plants Sampled	2,4-Dichlorophenol (average conc. µg/l)	2,4,6-Trichlorophenol (average conc. µg/l)
Pulp & Paper			
Alkaline Market	2	3	4.5
Alkaline BCT	2	4	1
Alkaline Fine	3	ND	ND
Alkaline Unbleached	1	ND	ND
Sulfite dissolving	1	1	5
Sulfite Paperbark	5	21	42
Timber			
Wood preserving steaming	2	Trace	ND
Barking	2	3,200	3,000
Finishing	3	233	64
Veneer, Plywood	3	84,000	ND
Leather Tanning	16	1,100	8
Steam Electric	20	ND	
Textiles			
Woven Fabric	3	ND	19
Stock & Yarn	7	ND	11
Paint & Ink	22	ND	2,400
Autos & Other Laundries			
Industrial	13	Trace	ND
Power	3	10	ND
Pesticides Mfg.	27	ND	526

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[a] 2-chlorophenol was not detected in any of the plants sampled.

ND - Not Detected.

Source: U.S. EPA (1980d).

TABLE 3-6. ESTIMATED SUPPLY AND DEMAND FOR PENTACHLOROPHENOL (kkg)

	1960	1965	1970	1973	1974	1975	1976	1977	1978	1979	1981
Capacity	NE[a]	25,400	NE	35,400	31,300	33,100	33,100	33,100	27,700	27,700	NE
Production	17,800	19,800	21,400	21,100	23,700	17,900	19,900	20,400	21,300	NE	NE
Demand	17,800	19,800	21,400	21,100	23,700	17,900	20,000	21,300	21,300	21,300	21,300

---

[a] NE - Not Estimated.

Source: JRB Associates (1980).

Through association, the production trends of the lower chlorophenols may be expected to parallel those of pentachlorophenol. These extrapolations are subject to an unknown amount of error, however, because production trends for pentachlorophenol may not be reflective of future trends for other chlorophenol-derivative compounds.

3.6 SUMMARY

Although production data on the three chlorophenols are not within the realm of published information, reasonable production quantities can be inferred based on the production of related compounds. These compounds and their derivatives are produced in relatively small quantities. Apparently, their derivatives have significant end-use applications, but only small amounts of the compounds themselves are isolated for consumption.

Intentional discharges are the major source of these compounds to the environment because they are not naturally occurring. Dispersion of these compounds in the biosphere is probably due to the degradation of derivatives and of other organic compounds in the environment. The rate of degradation of these substances would be variable and has not been adequately studied to estimate loadings of chlorophenols to the environment from most of these sources.

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4.0. FATE AND DISTRIBUTION OF CHLOROPHENOLS IN THE ENVIRONMENT

4.1 SUMMARY

This chapter describes the fate pathways and ultimate distribution of 2-chlorophenol (2-CP), 2,4-dichlorophenol (2,4-DCP), and 2,4,6-trichlorophenol (2,4,6-TCP) in environmental media following the intentional discharge or accidental release of these compounds to water, air, and soil. Laboratory and field data on the chlorophenols, when available, were used in this analysis. However, because of the limited available data base, estimates of environmental behavior were also made on the basis of the compounds' physical and chemical properties and extrapolations from structurally similar compounds. Monitoring data are presented from STORET and other surveys to provide indications of concentrations actually detected in environmental media.

The majority of chlorophenol entering the environment is discharged to water, primarily by chemical producers. Following release, adsorption, volatilization, and biodegradation are expected to be primarily responsible for removal of chlorophenols from the water column. Adsorption onto organic matter appears to be more significant than adsorption onto clay material, and, based on their octanol/water partition coefficients, trichlorophenol is more likely to be sorbed than are the lower chlorinated phenols. Volatilization to the atmosphere of the soluble fraction of chlorophenols is likely based on the compounds' high vapor pressures, especially the mono- and dichlorophenols. No actual measurements of volatilization from water were available to confirm its significance as a transport process for chlorophenols. Biodegradation is an important transformation process, especially for the lower chlorophenols. Acclimated microbial cultures can reduce mono- and dichlorophenol concentrations to negligible levels on the order of one week under laboratory conditions. Aquatic species may bioaccumulate all three chlorophenols to levels 100 to 400 times above concentrations.

Dichlorophenol is released to soil through the application of the herbicide 2,4-D and an unknown amount of all the chlorophenols enters the soil as impurities or breakdown products of 2,4-D, 2,4,5-T, silvex, and other pesticides. The movement of chlorophenols is controlled by adsorption onto organic matter and, apparently less importantly, sorption onto bentonite and other clays. The sorption bond is hypothesized to be weak and the lower chlorophenols to be easily desorbed by water, based on observations of acidic pesticides. Biodegradation is an important removal process for chlorophenol in soil, as it is in water. Soil populations can significantly reduce chlorophenol concentrations on the order of weeks and in even less time following acclimation. In porous soils and conditions unfavorable to biodegradation, there is a potential for migration of chlorophenols into groundwater. In agricultural areas, runoff and sediment transport are likely to transfer chlorophenols from soil to surface water, especially immediately after their application to land.

Very little is known about the atmospheric fate of chlorophenols following emission. The total amount of chlorophenols released to air each year is small, however, compared to other better characterized environmental compartments. There were no monitoring data available for any of the chlorophenols to indicate their presence in ambient air. Based on their physical and chemical properties, the chlorophenols are estimated to have an atmospheric half-life of roughly three weeks controlled by free radical oxidation. This estimate, however, has not been validated in the laboratory or under field conditions. Little is known about other atmospheric fate processes.

Secondary treatment is very effective at removing chlorophenols from wastewater, especially if well acclimated microbial populations are present. Inhibitory levels in each activated sludge for 2,4-DCP and 2,4,6-TCP have been reported at 200 mg/l. Other commonly employed treatment techniques, such as in primary treatment, do not appear to be very effective at chlorophenol removal.

Monitoring data on chlorophenol concentrations in environmental media are very few and limited to surface water. According to the STORET data base, the total of 300 ambient samples for chlorophenols were all at or below the detection limit (usually 10 μg/l, occasionally 100 μg/l). Concentrations in an effluent from a chemical plant ranged from 3 mg/l to 73 mg/l for the three chlorophenols. No measurements of chlorophenols in air or soil were available.

4.2 PHYSICAL AND CHEMICAL PROPERTIES

The environmental fate of 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol is dependent upon the compounds' physical and chemical properties. Table 4-1 lists some basic properties of the chlorophenols which are used in the subsequent analysis. In general, the chlorophenols can be characterized as weak acids with a relatively low solubility decreasing with chlorination and a high volatility at ambient temperatures (Kozak *et al*. 1979).

4.3 ENVIRONMENTAL PATHWAYS

4.3.1 Introduction

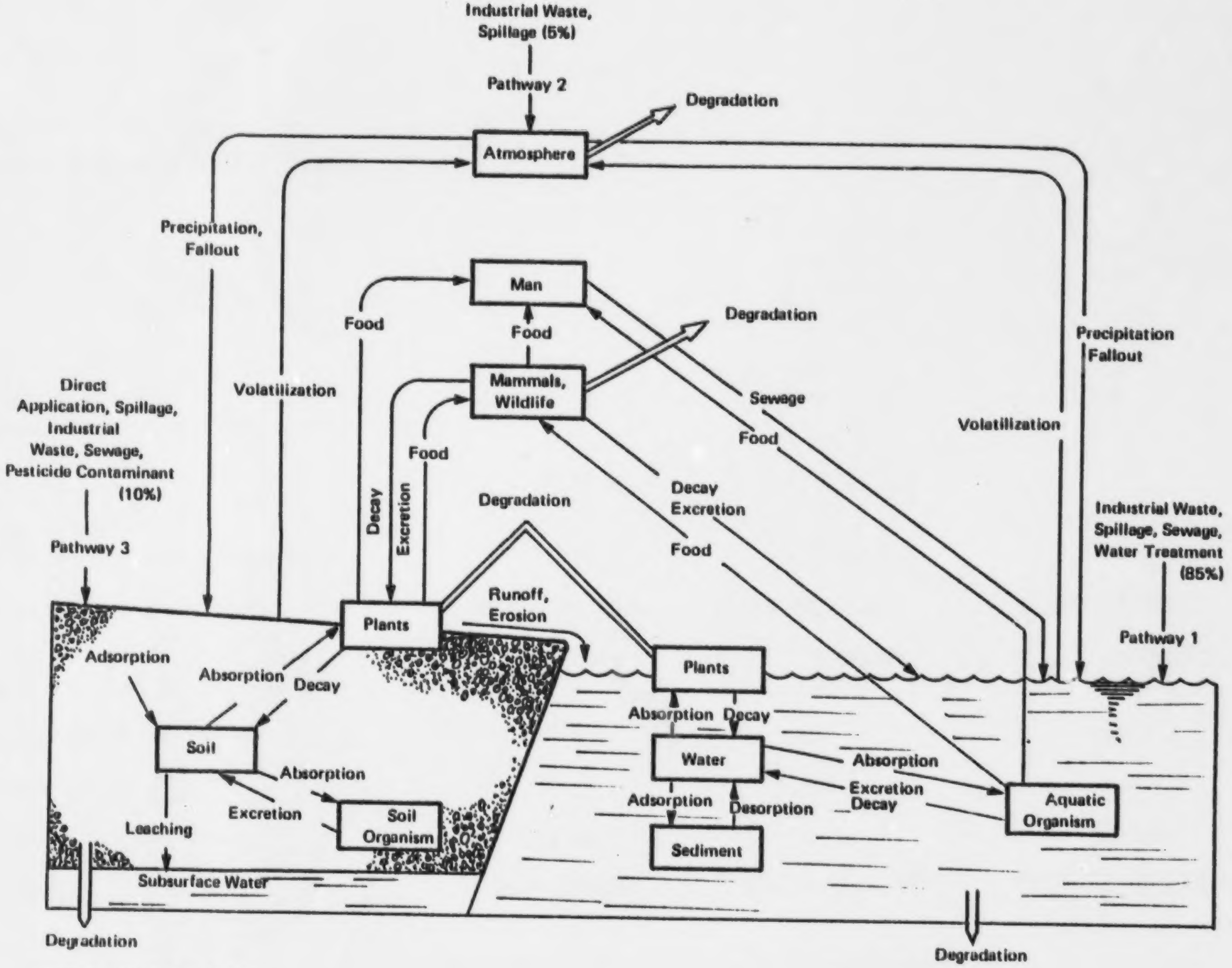
Figure 4-1 depicts the potential environmental pathways for chlorophenols from release into soil and water, and up to the point of exposure of receptors. Only the major pathways are considered in this chapter, with emphasis on the initial behavior of the pollutants in the vicinity of the point of release. Transfers between environmental compartments are only briefly considered.

Releases to water make up the most significant fraction of environmental releases as estimated in Chapter 3.0. This pathway is described in Section 4.3.2, Discharges to Surface Water. The atmosphere and land combined receive an estimated 15% of the environmental releases of chloro-

TABLE 4-1. PHYSICAL AND CHEMICAL PROPERTIES OF 2-CHLOROPHENOL, 2,4-DICHLOROPHENOL, AND 2,4,6-TRICHLOROPHENOL

Properties	2-Chlorophenol	2,4-Dichlorophenol	2,4,6-Trichlorophenol
Molecular Weight (gms)	128.56	163.01	197.46
Melting Point (°C)	8.7	45	68
Boiling Point at 760 mm Hg (°C)	175.6	206	244.5
Vapor Pressure at 20°C (mm Hg)	2.2	0.11	0.027
(atm)	0.0029	0.00014	0.000036
Solubility in Water (mg/l)	28,500 at 20°C	4,600 at 20°C	800 at 25°C
Log Octanol/Water Partition Coefficient	2.17	2.75	3.69
pKa	8.49	7.4	6
Saturated Vapor Concentration at 20°C,			
mg/m^3	16,600	1,060	310
mg/l	3,100	156	38

Source: Callahan *et al*. (1979), Kozak *et al*. (1979).


Industrial Waste, Spillage (5%)
Pathway 2
Degradation
Atmosphere
Precipitation, Fallout
Volatilization
Man
Food
Food
Degradation
Mammals, Wildlife
Food
Decay
Excretion
Direct Application, Spillage, Industrial Waste, Sewage, Pesticide Contaminant (10%)
Pathway 3
Degradation
Sewage
Food
Decay Excretion
Food
Precipitation Fallout
Volatilization
Industrial Waste, Spillage, Sewage, Water Treatment (85%)
Pathway 1
Plants
Runoff, Erosion
Adsorption
Absorption
Decay
Soil
Absorption
Excretion
Leaching
Soil Organism
Subsurface Water
Degradation
Plants
Absorption
Decay
Water
Absorption
Excretion Decay
Aquatic Organism
Adsorption
Desorption
Sediment
Degradation

Source: Kozak *et al.* (1979)

FIGURE 4–1 POSSIBLE CYCLING OF CHLOROPHENOLS IN THE ENVIRONMENT

phenols and are described in Emissions to Air (Section 4.3.3) and Land Disposal (Section 4.3.4). Additionally, in Pathway 4, a brief description of the wastewater treatment of cholrophenols is presented (Section 4.3.5).

4.3.2 Pathway 1: Discharges to Surface Water

The majority (85%) of known environmental emissions of all chlorophenols is released to surface water, primarily from production processes of the compounds themselves and their derivatives. Runoff from agricultural areas may also contribute to the total releases. Following release, the chlorophenols may be present in solution or adsorbed onto suspended and settled sediment. Since the chlorophenols are weak acids, the soluble fraction would tend to ionize, with dissociation increasing as the pH increases above pH 5 (Cserjesi 1972). The degree of dissociation would be expected to control adsorption onto colloids (Kozak et al. 1979). In primary treatment processes, chlorophenols are sorbed poorly to particulate matter (Kozak et al. 1979). Aluminum and ferric sulfate flocculents are especially ineffective at removing 2,4-dichlorophenol from water (Aly and Faust 1964). Through inference, a similarly low affinity for suspended particulates is also probable in natural aquatic systems.

The persistence of cholorophenols in surface water is dependent on certain fate processes resulting in transfer of the compounds to other media (i.e., volatilization) or transformation within water (i.e., biodegradation).

This section describes the relative importance of various fate processes potentially influencing the aquatic concentrations and persistence of chlorophenols.

4.3.2.1 Oxidation

There is no information specific to chlorinated phenols in water regarding oxidation. Highly chlorinated organic compounds are known to be resistant to oxidation, even at extremely high temperatures in excess of typical environmental temperatures (Morrison and Boyd 1973). Therefore, it seems probable that at least 2,4,6-trichlorophenol will not undergo oxidation in surface waters.

Mono- and dichlorophenols may oxidize in water at a slow rate. Calculations from experimental data show a half-life for phenol, the parent compound, undergoing free radical oxidation by RO_2 to be nearly 20 hours. Since no specific information is available on 2-CP and 2,4-DCP, it may be assumed as a conservative estimate that these compounds oxidize in water at a similar rate, with a half-life of a day or more.

4.3.2.2 Photolysis

Experimental work by Aly and Faust (1964) and Yasuhara and coworkers (1977) has shown that 2-chlorophenol and 2,4-dichlorophenol photolyze under wave lengths of light shorter than 290 nm, the minimum wavelength of solar radiation at the earth's surface. Aly and Faust (1964) investigated the photolysis of 2,4-DCP under ultraviolet light in the short wavelength range by irradiating 2,4-DCP in aqueous solutions of varying pH. In a basic solution (pH 9.0), where 2,4-DCP is completely dissociated, the irradiation time required for 50% decomposition was two minutes. Conversely, in an acidic solution (pH 4.0), 2,4-DCP did not dissociate and the irradiation time required for 50% decomposition was 34 minutes.

Yasuhara and coworkers (1977) examined the photolysis of 2-chlorophenol. A 10-mg/l aqueous solution of 2-chlorophenol was irradiated at wavelengths between 250 nm and 290 nm and underwent decomposition of less than 20% in one hour.

Although the experimental data discussed above has shown that 2-chlorophenol and 2,4-dichlorophenol are capable of photolyzing in aqueous solution under specific conditions, it should be noted that the wavelengths tested are less than the minimum wavelength of sunlight. No information was available regarding the photolysis of these compounds under natural light, so photolysis cannot be assumed to be a major transformation process in water. No information was found on the photolysis of 2,4,6-trichlorophenol. However, if it is assumed that this compound behaves like 2,4-dichlorophenol and 2-chlorophenol, then photolysis by direct sunlight may not be an important factor in decomposition in water.

4.3.2.3 Hydrolysis

The information on hydrolysis of chlorinated phenols suggests that hydrolysis is not an important fate process. Phenols show high reactivity toward electrophilic substitution but are resistant to nucleophilic attack. Hydrolytic displacement of chlorine is unlikely due to the strength of the covalent bond that binds the substituent to the ring (Morrison and Boyd 1973). In order to break the bonds, high temperatures are required, generally higher than those typically found in bodies of water. Consequently, hydrolysis is not expected to be an important chemical process in the transformation of chlorinated phenols from water.

4.3.2.4 Volatilization

Despite a lack of data specifically concerning the volatilization of chlorinated phenols from water, an examination of their Henry's law constants, through which a compound can be classified as to its degree of volatility, suggests that volatilization is a significant fate process in the transfer of chlorinated phenols from water to air.

The Henry's law constant can be estimated using the following equation:

$$H = P_{vp}/S$$

where P_{vp} is the vapor pressure at 20°C in atmospheres and S is the solubility in water at 20°C in moles/m^3. Referring to Section 4.2 on the physical properties of chlorinated phenols, the Henry's law constant for 2-chlorophenols, 2,4-dichlorophenols, and 2,4,6-trichlorophenols can be calculated. The results are shown in Table 4-2.

TABLE 4-2. HENRY'S LAW CONSTANTS FOR 2-CHLOROPHENOL, 2,4-DICHLOROPHENOL, and 2,4,6-TRICHLOROPHENOL

Compound	Vapor Pressure (atm)	Solubility (M/m^3)	H ($atm\text{-}m^3/M$)
2-Chlorophenol	0.0029	222	1.3×10^{-3}
2,4-Dichlorophenol	0.00014	28.2	5.0×10^{-6}
2,4,6-Trichlorophenol	0.000036	4.05	8.9×10^{-6}

A compound whose Henry's law constant is less than 3×10^{-7} atm-m^3/M is classified as volatile, 3×10^{-7} atm-m^3/M is classified as moderately volatile, and $H > 10^{-3}$ atm-m^3/M is classified as highly volatile (Mackay 1979) Mackay and Yuen 1979). Examination of the calculated values for H for 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol reveals that all three compounds would be classified as moderately volatile. An implication of this for river systems might be that these compounds volatilize out of water before a significant amount is transported downstream

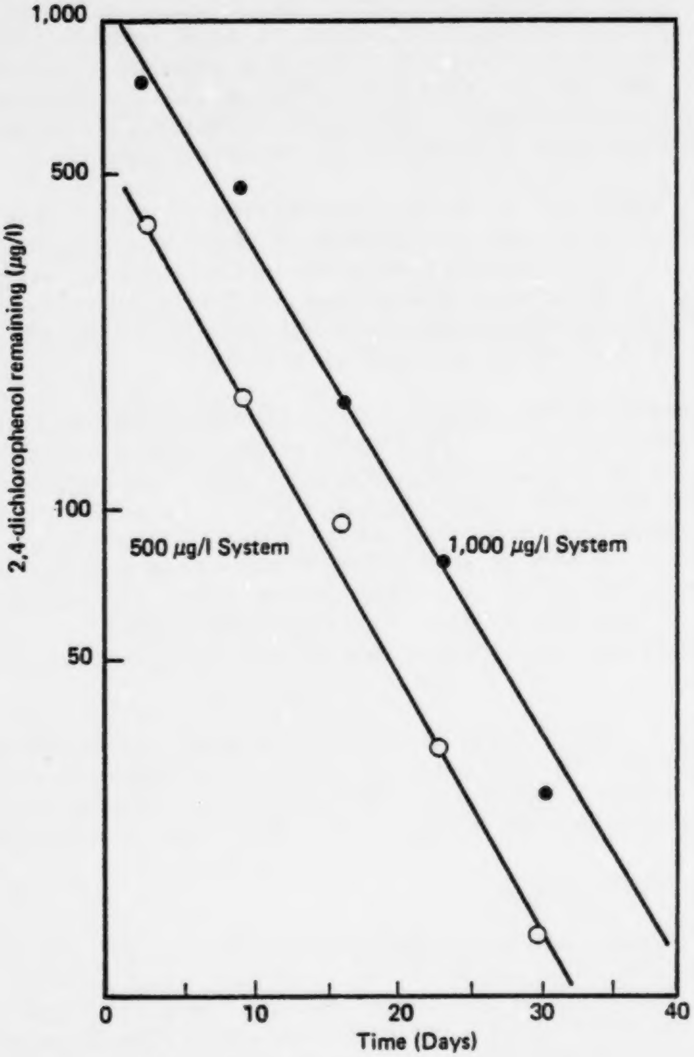
4.3.2.5 Biodegradation in Water

Aly and Faust (1964) investigated the biodegradation of 2,4-dichlorophenol in an aquatic system. To measure this process, solutions of 2,4-dichlorophenol in concentrations of 100 µg to 1,000 µg per liter were prepared using buffered natural lake waters and incubated under aerated conditions. As shown in Table 4-3, the 2,4-dichlorophenol was totally degraded within 9 days when the concentration was 100 µg/l. After 9 days, 66% of the 500-µg/l solution was oxidized by microorganisms, while only 54% was degraded in the 1,000-µg/l solution. Near complete degradation (97.5%) of the 500-µg/l and 1,000-µg/l solutions took place after 30 days. As shown in Figure 4-2, the overall biodegradation rate of the 500-µg/l and 1,000-µg/l solutions were equivalent; both decomposed 50% in six days.

Table 4-3. DEGRADATION OF 2,4-DICHLOROPHENOL IN AERATED AND BUFFERED LAKE WATERS

	Concentrations								
	100 μg/liter			500 μg/liter			1,000 μg/liter		
Time (Days)	pH	Concn	% Degd.	pH	Concn	% Degd.	pH	Concn	% Degd.
0	7.4	100	0.0	7.4	500	0.0	7.4	1,000	0.0
2	7.3	64	36.0	7.6	390	22.0	7.6	760	24.0
9	7.3	0	100.0	7.6	170	66.0	7.4	460	54.0
16	6.9	0	100.0	7.1	92	81.6	7.2	165	83.5
23	-	-	-	7.5	32	93.6	7.5	78	92.2
30	-	-	-	7.3	13	97.5	7.3	25	97.5

Source: Adapted from Aly and Faust (1964).



Source: Aly and Faust (1964)

FIGURE 4–2 **DISAPPEARANCE OF 2,4-DICHLOROPHENOL IN AN AERATED AND BUFFERED LAKE WATER**

To model the effect of decaying organic matter on the degradation rate, 2,4-dichlorophenol was added to unbuffered and unaerated lake water in the same concentrations outlined above. As shown in Table 4-4, 2,4-dichlorophenol never completely degraded, even at the lowest concentration. For the 100-µg/l solution, it took roughly two weeks for the concentrations to decompose by 50%. The same level of degradation was reached for the 500-µg/liter and 1,000-µg/liter solutions at roughly 18 and 44 days, respectively. Anaerobic, unbuffered conditions lengthened the degradation rate by a factor of three to eight.

In a comparison of the biodegradation of 1,000 µg/l 2-chlorophenol in polluted river water and in domestic sewage, the compound was found to degrade in 15 to 23 days in the river water culture, compared to little degradation in 30 days in the sewage culture (Ettinger and Ruchhoft 1950). The difference in degradation rate was attributed to the presence of an acclimated microflora in the polluted river.

In a static flask study with wastewater treatment microbial populations, 2-chlorophenol, 2,4-dichlorophenol and 2,4,6-trichlorophenol were reported to degrade 86%, 100%, and 100%, respectively, in 7 days in unacclimated cultures (Tabak et al. 1980). In acclimated cultures, all three compounds degraded >98% within 7 days. Therefore, there was little difference in the biodegradability of the three compounds. Acclimation did not appear to be an important factor under the simple laboratory conditions of the experiment. Only primary degradation was measured, so the identification and persistence of the intermediate metabolites is unknown.

Aquatic bacteria isolated from activated sludge systems have been shown to degrade chlorophenols as their sole carbon source or in the presence of other substances. The particular species which have been identified are described in Section 4.3.5 under wastewater treatment.

4.3.2.6 Bioaccumulation

Only limited data were available on the uptake and bioaccumulation of 2-CP, 2,4-DCP, and 2,4,6-TCP by fish and other aquatic organisms. Uptake of chlorophenols may occur through the gills, the gastrointestinal tract, or directly through the body surfaces. The factors which control rate and extent of uptake by aquatic organisms have not been determined (Kozak et al. 1979).

Flavor-impairment studies have shown that a variety of fish species experience tainting of the flesh at 2,4-DCP concentrations of 0.4 µg/l to 140 µg/l (U.S. EPA 1980a). Therefore, flavor impairment of fish appears to occur at lower concentrations than do toxic effects (see Chapter 6); concentrations of chlorophenols well below toxic effects levels in surface water may result in the contamination of sport fisheries based solely on organoleptic criteria although these criteria have no demonstrated adverse human health effects.

TABLE 4-4. DEGRADATION OF 2,4-DICHLOROPHENOL IN UNAERATED AND UNBUFFERED LAKE WATERS

	Concentrations								
	100 μg/liter			500 μg/liter			1,000 μg/liter		
Time (Days)	pH	Concn	% Degd.	pH	Concn	% Degd.	pH	Concn	% Degd.
0	7.3	100	0.0	7.3	500	0.0	7.3	1,000	0.0
3	6.2	80	20.0	5.1	390	22.0	4.1	780	22.0
7	6.1	70	30.0	6.1	380	24.0	6.0	770	23.0
14	-	-	-	-	-	-	6.1	620	38.0
17	7.9	40	60.0	6.5	253	49.4	6.3	560	44.0
24	-	40	60.0	-	192	61.6	-	540	46.0
43	-	20	80.0	-	192	61.6	-	506	49.4

Source: Adapted from Aly and Faust (1964).

An actual laboratory-derived measure of bioaccumulation resulting from a long-term controlled study is available only for 2-chlorophenol. Bluegill (Lepomis macrochirus) exposed for one month to 9.2 μg/l of 2-chlorophenol had a measured bioconcentration factor (BCF) of 214 (U.S. EPA 1980b) which would give a body burden of 2 mg/kg. Theoretically derived estimations of the BCF, based on the properties relationship to the octanol/water partition coefficient, were calculated for the other two chlorophenols (U.S. EPA 1980a, U.S. EPA 1980c). For 2,4-dichlorophenol the BCF was estimated to be 130, and for 2,4,6-trichlorophenol, 380.

In a second lab study, 2,4-dichlorophenol levels of 18 mg/kg were detected in the muscle of a European trout, Salmo trutta, after 24 hours exposure to 1.7 mg/l (Hattula et al. 1981). The concentration also resulted in mortality to 50% of the test population. The calculated BCF was 10, an order of magnitude below the estimated level; however, this difference may have been due to the short period of exposure..

In a field study, concentrations of 2,4,6-trichlorophenol were measured in the liver and body fat of rainbow trout exposed to diluted kraft pulp bleachery effluents following effluent pretreatment (Landner et al. 1977). Concentrations ranged from 2 mg/kg to 45 mg/kg in the liver after exposure for 2 to 11 weeks. The range was dependent on the pretreatment techniques. Muscle levels measured less than 1 mg/kg after 11 weeks exposure. Perch and northern pike caught in the vicinity of the same pulp mill had 2,4,6-trichlorophenol concentrations in the liver fat of 2.7 mg/kg and 0.4-0.5 mg/kg, respectively (Landner et al. 1977).

The compound 2-chlorophenol has a rapid depuration rate with a half-life of less than one day (U.S. EPA 1980b) presumably due to rapid metabolism. The observed rate of clearance for 2,4,6-trichlorophenol in rainbow trout suggests a tentative biological half-life in the liver of less than 10 days (Landner et al. 1977). No information was available on the clearance rate for 2,4-dichlorophenol.

The available data do not provide any evidence of differences in bioaccumulation at lower versus higher trophic levels. It is not known whether biomagnification occurs with 2-chlorophenol, 2,4-dichlorophenol, or 2,4,6-trichlorophenol (Kozak et al. 1979).

4.3.3 Pathway 2: Emissions to Air

Only a small fraction, approximately 5%, of all known environmental releases of chlorophenols is emitted to the atmosphere. These releases are primarily in vapor form from production processes. Since very little is known about the atmospheric fate of chlorophenols (Kozak et al. 1979), the estimates presented in this section cannot be validated at this time and should be used with caution.

4.3.3.1 Free Radical Oxidation

No experimental evidence was found regarding the reaction of chlorinated phenols with free radicals in the atmosphere. Nevertheless, estimations of the relative reactivity of chlorinated phenols with free radicals can be made based on compounds, such as phenol, close in structure to chlorinated phenols. Phenol has a low value for the hydroxyl radical reaction rate constant, k_{OH}, such that:

$$k_{OH} < 5 \times 10^{10} \ \frac{cm^3}{mole\ sec}$$ (Hendry and Kenley 1979)

Combing this rate constant with the average value of the concentration of OH in the atmosphere estimated by Neely and Planka (1978) (i.e., 8×10^{-18} M/cm^3), the rate of oxidation due to hydroxyl radical attack can be estimated to be:

$$5 \times 10^{10} \times 8 \times 10^{-18} = 4 \times 10^{-7} \ sec^{-1}$$

The total rate of oxidation is the sum of the rate of oxidations due to hydroxyl radicals and to ozone. Values for the ozone reaction rate constant for phenol or for any of the chlorinated phenols addressed in this report are not presently available. However, for many aromatic hydrocarbons the reaction rate due to ozone is much smaller than the reaction rate due to hydroxyl radicals (Hendry and Kenley 1979) such that the ozone reaction rate constant, K_{O3}, multiplied by the average ground level ozone concentration (1.6×10^{-12} M/cm^3) is much less than the oxidation reaction rate due to hydroxyl radicals.

Assuming this to be true for the phenols as well, the rate of oxidation is governed by the rate of oxidation due to hydroxyl radical attack. Therefore, the half-life of these compounds in the atmosphere undergoing oxidation is estimated to be:

$$t_{1/2} = \frac{0.693}{k_{ox}} \cong 20 \ days$$

where $k_{ox} = 4 \times 10^{-7} \ sec^{-1}$

Assuming that the hydroxyl radical reaction rate constant for chlorinated phenols is equivalent to that for phenol, chlorinated phenols emitted into the atmosphere have a half-life of roughly three weeks.

4.3.3.2 Atmospheric Photolysis

All of the information found concerning the photolysis of 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol pertained to photolysis in aqueous solution rather than to atmospheric photolysis. As discussed in Section 4.3.2.2, in aqueous solution the chlorinated phenols photolyze under wavelengths of light slightly below the minimum wavelength of natural sunlight. Based on these very limited data, atmospheric photolysis does not appear to be a significant fate process since the chlorophenols do not absorb UV light in the >290-nm wavelength region characteristic of solar radiation.

4.3.4 Pathway 3: Land Disposal

Direct releases of chlorophenols to soil in disposal of solid waste are expected to be minimal relative to aquatic discharges. Waste disposal of chlorophenols combined with 2,4-dichlorophenol releases associated with the application of the herbicide 2,4-D are estimated to comprise approximately 10% of the total annual environmental discharges of chlorophenols. In this section, the influence of biodegradation, sorption, and bioaccumulation on the concentrations of chlorinated phenols in the soil will be discussed.

4.3.4.1 Sorption

The ability of a soil to sorb chemical compounds is dependent upon the clay and organic content of the soil. Aly and Faust (1964) investigated the capability of clay to adsorb 2,4-dichlorophenol using three different clay types: bentonite, kaolinite, and illite. All clay sorbed 2,4-dichlorophenol to a small degree and the amount sorbed was directly related to the surface area of the clay material. Kaolinite and illite are non-expanding lattice materials low in surface area and thus limited in their ability to sorb dichlorophenol. Bentonite, an expanding lattice material, has a greater surface area and a consequent ability to sorb dichlorophenol.

The adsorptive capacity of a soil is also dependent upon the soil's organic content and the compound's hydrophobic tendency as indicated by its octanol/water partition coefficient. If the log octanol/water partition coefficient is greater than unity, the compound will preferentially partition into the soil organic matter. Although this is not a completely reliable correlation it may be used as a rough guide. The compounds 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol have log octanol/water partition coefficients greater than 2, which shows that the ratio of the affinity of these compounds to bind to organics versus water is greater than 100 to 1. If the chlorinated phenols are present in soils that are high in organic content, it may be suspected that they will bind to the soil particles. Mineral soils, low in organic matter, would not be expected to significantly sorb chlorinated phenols.

Although some soils may adsorb chlorinated phenols, the fact that 2,4-dichlorophenol has been found in groundwater in areas near large deposits of 2,4-dichlorophenol waste and the fact that large quantities of clay were required to sorb even small amounts of 2,4-dichlorophenol in the experiments by Aly and Faust (1964) imply that large quantities of this compound may exceed the sorption capability of some soil types, leading to the possibility of groundwater contaminations. Consequently, although small amounts of chlorinated phenols deposited on soil may satisfactorily be sorbed by the soil, larger quantities associated with waste disposal or application of derivative pesticides may result in seepage through the soil column into the groundwater table.

4.3.4.2 Biodegradation in Soil

As described in Section 4.3.2.5, microbial degradation of chlorophenols in aquatic systems is a significant transformation process. Several studies have also investigated biodegradation specifically in soil systems.

Walker (1954) compared the rate of degradation of 2-chlorophenol to investigate the influence of population acclimation on the rate of degradation. Approximately two-thirds of an initial dosage of 1.0 gram 2-chlorophenol disappeared within 10 days of application to a light clay soil (pH 6.8). Subsequent applications, however, required only 5 days to disappear, a significant increase in the rate of degradation. Walker concluded that rapid dissipation of 2-chlorophenol was the result of an acclimated bacterial population. Acclimated microorganisms were also shown to be highly effective in the removal of both 2-chlorophenol and 2,4-dichlorophenol by Alexander and Aleem (1961).

Several investigations have identified specific microorganisms capable of biodegrading chlorophenols. Spokes and Walker (1974) showed that phenol-grown Nocardia sp., Pseudomonas sp., Mycobacterium coelicium, and Bacillus sp. oxidized 2-chlorophenol, resulting in the formation of 3-catechol. Evans et al. (1971) showed that Pseudomonas sp. also degraded 2,4-dichlorophenol. This was elucidated by studying the biodegradation pathway of the pesticide 2,4-D, a pathway consisting of cleavage of the ether bond, forming 2,4-dichlorophenol, 3,5-dichlorocatechol, and α-chloromuconate, which are further metabolized to release Cl^- and other unidentified metabolites (Evans et al. 1971). The compound 2-chlorophenol was hypothesized to be formed via a nonoxidative elimination of chlorine from 2,4-dichlorophenol or directly from 2,4-D. Ring ortho-hydroxylation via oxidation by microorganisms transformed 2-chlorophenol to 3-chlorocatechol which in turn degraded to α-chloromuconate. Bollag and coworkers (1968) examined a strain of Arthobacter sp. capable of converting 2,4-dichlorophenol to 3,5-dichlorocatechol through enzymatic hydroxylation in the presence of NADPH and oxygen.

Fungi have also been found to be capable of degrading chlorophenol. Lyr (1962) explained the ability of basidiomycetes to degrade chlorophenols by the presence of phenol oxidase. He found that the wood-rotting fungus Tramates vericolor was able to degrade chlorophenols via secretions of laccase, tyorosinase, and peroxidase. Walker also isolated fungi capable of degrading chlorophenols. The fungus isolated Rhodoturula glutinis, was able to use phenol as the sole carbon source, but required the presence of other substances.

4.3.4.3 Terrestrial Plants

There are no known intentional applications of any of the chlorophenols to terrestrial plants. Potential indirect sources to plants include the metabolism of derivative herbicides and irrigation by contaminated water.

Very limited information is available concerning direct uptake of chlorophenols by terrestrial plants. Oats and soybean roots rapidly absorbed 2,4-DCP from nutrient solution and soil and minimal translocation to the edible grain was observed in soybeans (Kozak et al. 1979).

Oats bioconcentrated 2,4-DCP to levels 9 times greater than the 0.2-μg/l concentration in the nutrient solution. Bioconcentration factors were less than one in the oats grown in soil and in the soybeans grown in solutions and soil (Kozak et al. 1979). No information was available regarding plant uptake of 2-chlorophenol or 2,4,6-trichlorophenol.

Residues of 2,4-dichlorophenol may appear in plants treated with the herbicide 2,4-D. Studies on rice, kidney beans, soybeans, peas, barley, timothy, and various grasses indicated metabolism of 2,4-D to dichlorophenol following shortly after herbicide application (Kozak et al. 1979, Steen et al. 1974). Plant levels are usually one to two orders of magnitude below the inital 2,4-D concentrations (Steen et al. 1974). In the rice plants, most of the dichlorophenol disappeared over the course of the growing season (Kozak et al. 1979). No information was available on the persistence of 2,4-DCP in other plant species. There is a possibility that 2-chlorophenol residues in plants may also accumulate from degradation of the herbicide 2,4-D (U.S. EPA 1980b). Potential sources of 2,4,6-trichlorophenol include lindane and possibly 2,4-5-T.

Based on the available data, contamination of food crops by chlorophenols does not appear likely to occur (Kozak et al. 1979; U.S. EPA 1980a, 1980b, 1980c).

4.3.4.4 Field Studies

There is evidence for the presence and persistence of chlorophenols in soil and groundwater. Swenson (1962) reported an incident occurring in California in 1945 where a chemical company manufacturing 2,4-D released 2,4-dichlorophenol into the city sewage system. The chemical ended up infiltrating downstream shallow wells within 3 weeks and odors and tastes persisted for 3 years. Walker (1961) reported on groundwater contamination resulting from the lagoon disposal of 2,4-D wastes at the Rocky Mountain Arsenal in Colorado. Crop damage was caused by use of irrigation water from a well downslope from the dumping sites at the arsenal. The compound was estimated to migrate 5.6 km in 7 to 8 years and to affect an area of 16.8 km^2. Direct contamination of soil is also likely due to the direct application of the herbicide 2,4-D on cropland, rangeland bush control, and right-of-ways. A Russian forest was aerially sprayed with 3 kg of 2,4-D and the soil was monitored for the metabolite 2,4-dichlorophenol. Detectable concentrations were found to persist for 60 to 90 days, staying in the top 50 cm of the soil (Motuzinskii 1975).

4.3.5 Pathway 4: Behavior of Chlorophenols in Wastewater Treatment

Chlorophenols are readily removed from water during secondary wastewater treatment, especially in well acclimated biological treatment systems. Haller (1978) found that a wastewater sludge supernatant completely removed a concentration of 16 mg/l of 2-CP over a period of 14 to 25 days. Sidwell (1971) studied the disappearance of 2,4-DCP from an aerated lagoon effluent.

The initial concentration of 2,4-DCP in the effluent, 64 mg/l, was nondetectable within five days.

The effect of pH, temperature, and chlorophenol concentrations on the biodegradability of these compounds in wastewater treatment was studied by Ingols and coworkers (1966). The optimal temperature for 2-CP degradation was found to be between 25°C and 27°C and the optimum pH between 6.5 and 8.0. Concentrations of 2,4-DCP and 2,4,6-TCP greater than 200 mg/l inhibited degradation significantly. Several studies have identified Pseudomonas sp. and Nocardia sp. as the aquatic microorganisms capable of degrading chlorinated phenols in wastewater treatment (Nachtigall and Butler 1974).

Primary treatment may not always be effective at removing chlorophenols because of their poor sorption by particulates and the apparent ineffectiveness of flocculants (i.e., aluminum or ferric sulfate) under certain wastewater treatment conditions (Kozak et al. 1979).

Little information was available concerning the effectiveness of other treatment methods. Activated carbon adsorption and strongly basic anion-exchange resin techniques appear to effectively reduce 2,4-dichlorophenol concentrations in water (Kozak et al. 1979). Chemical oxidation is also practiced at some plants to remove chlorophenol tastes and odors. Lower chlorophenols are chlorinated to higher chlorinated products such as 2,4,6-trichlorophenol,which subsequently undergoes ring oxidation to form carboxylic acids and other products (Kozak et al. 1979).

4.4 MONITORING DATA

With the exception of pentachlorophenol, comprehensive monitoring data on the chlorophenols are scarce for water and practically non-existent for air, soil, and biota. In addition to a lack of adequate studies, a number of those completed to date have aggregated (or failed to disaggregate) the data under the more general categories of total phenols or chlorophenols. The most frequently observed compound of the three is 2,4-dichlorophenol, most likely due to its occurrence in the pesticide 2,4-D. There are no monitoring data available for any of these compounds in the atmosphere; conjecture would indicate potential sources of atmospheric pollution as chemical manufacturing plants incineration of trash containing these products, and volatilization from water and soil. There is a similar lack of data for biota in the literature and also within the STORET data base (U.S. EPA 1979). All available data for biota are discussed under Pathways 1 and 2.

4.4.1 Methods of Analysis

Until 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol were identified as priority pollutants, the method most commonly used for identification of these compounds was measurement of total phenols or at best of total chlorophenols. The 4-aminoantipyrine colorimetric method (4-AAP) is a typical non-specific method which estimates the total concentration of chlorophenols (Buikema et al. 1979, Kozak et al. 1979). Recently, however, there has been an effort to distinguish between different phenols using electron-capture gas-liquid chromatography. This change in focus means that historical and recent monitoring data are not comparable, which prevents analysis of long-term trends in environmental concentrations. Additionally it means that the monitoring data base, being relatively new, is very limited for each of the chlorophenol compounds.

4.4.2 Water

4.4.2.1 STORET Data Base

STORET data are too limited to draw conclusions on the distribution and magnitude of concentrations of chlorinated phenols in U.S. ambient waters (U.S. EPA 1979); sampling of chlorophenols has occurred in only seven major river basins since 1977. Because of this, it is more beneficial to examine water quality conditions on a local level for the following water regions: Ohio River, Upper Mississippi River, Lake Michigan, Missouri River, Lower Mississippi River, Western Gulf, and Pacific Northwest (see Table 4-5). Concentrations for the three chlorophenols were undetectable in the Western Gulf region.

Virtually all of the observations (roughly one hundred for each chlorophenol) are remarked data. It should be noted that the distribution of observations is nearly identical among the three chlorophenols, as depicted in Table 4-5, and may be indicative of a standard detection limit for all three compounds. The unremarked data were too limited to indicate any patterns in concentration distribution. Since remarked data are equal to or below the detection limit, these data tend to overestimate the actual concentrations of chlorophenols present at a location. This should be considered in any analysis of these data.

For 2-chlorophenol nearly all observations taken in the Ohio, Upper and Lower Mississippi, and Missouri Rivers fall in the inclusive range of 1.1 to 10 μg/l and 10.1 to 100 μg/l. Seventy-one percent of the observations in the Pacific Northwest region appear in the range of 10.1 to 100 μg/l, with the remaining 29% between 1.1 to 10 μg/l. In combining all observations of 2-chlorophenol, 3% are between 0.1 to 1 μg/l, 57% between 1.1 to 10 μg/l, and 40% between 10.1 to 100 μg/l. The mean values of the seven river basins ranged from 0.0 to 50 μg/l over the three year period and centered around 10 μg/l.

Results for 2,4-dichlorophenol are very close to those for 2-chlorophenol. Virtually all observations taken in the Ohio, Upper and Lower Mississippi, and Missouri Rivers appear in the range of 1.1 to 10 μg/l. Seventy-five percent of the observations for Lake Michigan are in the range of 0.1 to 1 μg/l, with the remaining percentage in the range of 10.1 to

TABLE 4-5. CHLORINATED PHENOLS IN AMBIENT WATERS-STORET DATA (1977-1979)
(µg/l)

Region	2-Chlorophenol				2,4-Dichlorophenol				2,4,6-Trichlorophenol			
		Percentage of Observations				Percentage of Observations				Percentage of Observations		
	Number of Observations	0.1-1	1.1-10	10.1-100	Number of Observations	0.1-1	1.1-10	10.1-100	Number of Observations	0.1-1	1.1-10	10.1-100
Ohio River	6		100		6		100		6		100	
Upper Mississippi River	5		100		5		100		5		100	
Lake Michigan	6	50		50	12	75		25	12	50	25	25
Missouri River	27,1[a]		96	4	28		96	4	27.1[a]		96	4
Lower Mississippi River	5		100		5		100		5		100	
Pacific Northwest	51		29	71	51		29	71	51		29	71
UNITED STATES	100,1[a]	3	57	40	107	8	54	37	106,1[a]	6	57	37

[a] Unremarked data.

Source: U.S. EPA (1979).

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100 μg/l. As with 2-chlorophenol, 71% of the observations in the Pacific Northwest region for 2,4-dichlorophenol fall between 10.1 to 100 μg/l, with the remainder between 1.1 to 10 μg/l. To combine all observations for 2,4-dichlorophenol, the distribution results are 8% of the observations between 0.1 to 1 μg/l, 54% between 1.1 to 10 μg/l, and 37% between 10.1 to 100 μg/l. From 1977 to 1979, the mean values of the regions reporting ranged from 0.0 to 30 μg/l and centered around 10 μg/l.

For 2,4,6-trichlorophenol, 50% of the observations appear between 0.1 to 1 μg/l; the remaining percentage is divided equally between the ranges of 1.1 to 10 μg/l and 10.1 to 100 μg/l. The distribution of observations for other basin regions is identical to those for both 2-chlorophenol and 2,4-dichlorophenol. An aggregation of the observations for 2,4,6-trichlorophenol results in a distribution of 6% in the range of 0.1 to 1 μg/l, 57% between 1.1 to 10 μg/l, 37% between 10.1 to 100 μg/l. The mean values of 2,4,6-trichlorophenol for the seven basins ranged from 0.0 to 30 μg/l and centered around 10 μg/l.

4.4.2.2 Other Water Monitoring Data

Jungclaus and coworkers (1978) studied the wastewater and receiving water and sediments at a specialty chemicals manufacturing plant producing a broad range of chemicals for use in other industries. In the plant wastewater levels ranging from 10 to 20 μg/l of chlorophenol were reported. A non-quantifiable amount was present in the river water but was not detected in the sediment. In addition, dichlorophenol was detected in wastewater and river water, but was not quantified.

In a study of the wastes from the manufacture of herbicide, particularly 2,4-D and 2,4,5-T in a Jacksonville, Arkansas plant, Sidwell (1971) reported levels of 2.88, 73.16, and 2.78 mg/l for 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol, respectively. Kawahara (1971) reported detectable levels of 2,4-dichlorophenol in the Ohio River and at a dam in West Virginia, and a level of 6.6 μg/l at an intake for the Cincinnati water supply. The median concentration of 2,4-dichlorophenol for drinking water supplies for all cities examined in the National Organic Monitoring Survey was 0.02 to 0.05 μg/l. The mean was 0.18 μg/l for 80% of the cities detecting this compound (U.S. EPA 1975).

In a Swedish study of chlorophenols in the spent bleach liquors produced at several kraft pulp mills, Lindstrom and Nordin (1976) found detectable but non-quantifiable levels of dichlorophenol. For 2,4,6-trichlorophenol reports of 25 μg/l in the chlorination stage and 1,150 μg/l in the extraction stage were made. In the pulp, 0.9 μg/ton in the chlorination stage and 1.8 g/ton in the extraction stage were reported. (These results are for one of three mills; results from the three were in close agreement).

The Rhine River and other Dutch surface waters were sampled for chlorophenol content in a two-year monitoring study (January 1976 through December 1977) reported by Wegman and Hafstee (1979). A total of 206 samples were taken at 6 sampling sites. For the Rhine, levels of the three compounds decreased in both frequency and concentration over the sampling period; this trend also applied to the Meuse River. However, the Boven Merwede and the Ijssel Rivers both showed slight increases in the levels of 2,4,6-trichlorophenol in 1977. An earlier study encompassing many of the same water bodies was reported by Piet and De Grunt (1975) and showed significantly higher levels for these three compounds. From these results it appears that increasingly stringent regulations have contributed to an appreciable decrease in chlorophenol pollution in the Netherlands.

Summaries of concentrations of chlorophenols reported in the literature are presented in Tables 4-6 and 4-7.

TABLE 4-6. REPORTED CONCENTRATIONS OF CHLORINATED PHENOLS IN THE ENVIRONMENT

Compound	Concentration (mg/l)	Comment	Reference
Chlorophenol	D[a]	river	Jungclaus *et al*. (1978)
Chlorophenol	0.01-0.02	wastewater from chemical producer	Jungclaus *et al*. (1978)
Dichlorophenol	D	river	Jungclaus *et al*. (1978)
Dichlorophenol	D	wastewater from chemical producer	Jungclaus *et al*. (1978)
2-Chlorophenol	0.0017	secondary sewage effluent	Jolley *et al*. (1975)
2,4,6-Trichlorophenol	D	pulp mill effluent (Sweden)	Landner *et al*. (1977)
2-Chlorophenol	2.88	herbicide production waste	Sidwell (1971)
2,4-Dichlorophenol	73.16	herbicide production waste	Sidwell (1971)
2,4,6-Trichlorophenol	2.78	herbicide production waste	Sidwell (1971)
2,4-Dichlorophenol	0.00018	urban drinking water	U.S. EPA (1980a)

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[a] D = detected but non-quantifiable

TABLE 4-7. CHLOROPHENOLS IN RIVER WATER (μg/1) NORTHERN EUROPE

	1974[a]	1976[b]			1977[b]		
	Mean	Frequency of Detection (%)[c]	Max.	Med.	Frequency of Detection(%)	Max.	Med.
2-Chlorophenol							
Rhine	3-20	2	2.3	ND	0	ND	ND
Meuse (at Eijsden)	2-20	0	ND	ND	0	ND	ND
2,4-Dichlorophenol							
Rhine	0.03-1.5	47	0.59	ND	48	0.35	ND
Meuse (at Eijsden)	0.01-0.04	0	ND	ND	0	ND	ND
2,4,6-Trichlorophenol							
Rhine	0.07-0.1	94	2.5	0.19	87	0.51	0.18
Meuse (at Eijsden)	0.003-0.02	30	0.05	ND	23	0.05	ND
Boven Merwede		92	0.27	0.12	92	0.37	0.15
Ijssel		92	0.35	0.18	92	0.37	0.16
Meuse (at Lith)		27	0.12	ND	31	0.04	ND

---

[a] Piet and De Grunt (1975).

[b] Wegman and Hafstee (1979).

[c] Out of a total of 206 grab samples.

ND = Not detected.

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5.0. EFFECTS AND EXPOSURE--HUMANS

5.1 SUMMARY

The available data on the toxicity of 2-chlorophenol (2-CP), 2,4-dichlorophenol (2,4-DCP), and 2,4,6-trichlorophenol (2,4,6-TCP) are limited. As a group, these compounds appear to be readily metabolized and excreted in urine as glucuronide and sulfate conjugates; supporting data, however, are scanty. Acute median lethal doses of 2-CP and 2,4,6-TCP are in the 100 to 900 mg/kg range; 2,4-DCP is somewhat less toxic. Subacute studies are few, but alteration of liver function appears to be the principal finding. All three compounds have been shown to inhibit oxidative phosphorylation in rat liver mitochondria in vitro.

Dietary administration of 2,4,6-TCP is carcinogenic in male F344 rats, inducing lymphomas or leukemias. This compound is also carcinogenic in both sexes of B6C3F1 mice, inducing hepatocellular carcinomas or adenomas. The carcinogenicity of 2,4-DCP and 2-CP has not been examined by the oral route, although both compounds do possess tumor-promoting activity in mice. The trichlorinated 2,4,6-TCP is inactive in this respect.

Chromosomal damage in mammalian somatic tissues was induced by 2-CP treatment; available data on 2,4-DCP and 2,4,6-TCP are insufficient to evaluate the mutagenicity of these compounds. There is no information available on the effects of 2-CP, 2,4-DCP, or 2,4,6-TCP on the developing embryo.

An estimation of the risk to man associated with exposure to 2-CP and 2,4-DCP cannot be adequately made due to the lack of available toxicological data on these compounds, particularly with respect to long-term effects in experimental animals and/or human exposure.

The limited information available suggests that human exposure to chlorinated phenols is low. The most common route of exposure appears to be in drinking water, with 2,4-dichlorophenol detected at low levels in numerous drinking water samples. Maximum exposures of 60-100 µg/day were estimated for the three compounds considered, based on concentrations in unfinished drinking water, with a more typical exposure of 0.4 µg/day for 2,4-DCP. Typical exposures for 2-chlorophenol and 2,4,6-TCP are unknown, but may be lower than that for 2,4-DCP due to the lower likelihood of their entering the environemnt.

Exposure of humans through seafood has a potential on the order of 1 mg/day, but this estimate is highly speculative, and few actual residues have been reported in fish. In fact, metabolic data for fish indicate a rapid excretion of at least chloro- and dichlorophenols. The use of other products (2,4-D, 2,4,5-T) may result in exposure to the chlorophenols, however, such exposure cannot be quantified due to a lack of information on use patterns, exposure concentrations, and other parameters.

Inhalation exposure to chlorinated phenols is unknown, but based on the limited information available, it is probably less significant than other routes of exposure.

5.2 HUMAN TOXICITY

5.2.1 Introduction

Chlorinated phenols are commercially important intermediates in the synthesis of dyes, pigments, phenolic resins, pesticides, herbicides, etc. Human exposure is therefore predominately occupational in nature. However, their direct use as antiseptics, disinfectants, and fungicides, as well as their presence in drinking water, can result in exposure of the population at large. This section of the report will examine the somewhat limited data available on the toxicity of 2-chlorophenol, 2,4-dichlorophenol, and 2 4,6-trichlorophenol to mammalian species.

5.2.2 Metabolism and Bioaccumulation

Little information is available on the metabolic pathways of chlorinated phenols in experimental animals or in man. The lipophilic nature and low degree of ionization at physiological pH of 2-CP, 2,4-DCP, and 2,4,6-TCP suggest facile absorption of these compounds by all routes of entry. Penetration of 2,4-DCP and 2,4,6-TCP through intact, excised human skin has been demonstrated *in vitro* (Roberts *et al*. 1977), however, no quantitative data are available on the absorption and distribution of these compounds *in vivo*.

Data on the metabolism of these compounds are also sparse, but, in general, chlorinated phenols appear to be handled in a manner similar to phenol (i.e., conjugation with glucuronic acid and/or conjugation with sulfuric acid to form ethereal sulfates). In rabbits, doses of 150-300 mg/kg 2-CP produced 82% conjugated glucuronic acid and about 19% ethereal sulfate (Spencer and William 1950). Similar data have been reported for 2-CP in dogs (Karpow 1893) and 2,4-DCP in rabbits (Deichmann and Thomas 1943, Dodgson *et al*. 1950). Korte and coworkers (1978) reported rapid clearance of 2,4,6-TCP in rats fed 1 mg 2,4,6-TCP/kg diet for 3 days. Elimination occurred predominately in urine (82% of the administered dose), with a smaller amount in feces (22% of the administered dose). No radiolabelled 2,4,6-TCP was detected in liver, lung, or fat obtained five days after the last dose.

Exposure to other chemicals can also result in exposure to chlorophenols via metabolic degradation of the parent compound. Kohli and coworkers (1976) found 2,4,6-TCP to be a major urinary metabolite of rabbits exposed to 1,3,5-trichlorobenzene. Kurihara (1975) noted 2,4-DCP and its conjugates in the urine of mice given gamma- or beta- benzene hexachloride. In sheep and cattle fed the herbicide 2,4-dichlorophenoxyacetic acid (2.4-D) 2,4-DCP was found to be a major metabolite (Clark *et al*. 1975). Lindsay-Smith and coworkers (1972) reported 2-CP in the urine of rabbits given chlorobenzene, while Selander and coworkers (1975) noted the in vitro conversion of chlorobenzene to 2-CP by perfused rat livers. The above examples serve to demonstrate that exposure to chlorophenols can occur in mammals indirectly as a metabolite of other compounds, but these indirect routes do not appear to be a major route of exposure.

While highly lipophilic compounds, such as the chlorinated phenols generally accumulate in adipose tissue, there are no data available to suggest that bioaccumulation occurs. As stated earlier, Korte and coworkers (1978) found no radiolabelled 2,4,6-TCP in liver, lung, or fat of rats five days after oral exposure to 2,4,6-TCP, and Clark and associates (1975) detected less than 0.05 mg 2,4-DCP/kg tissue in both fat and muscle of sheep and cattle fed the herbicide 2,4-D (2,000 mg/kg diet) for 28 days. Tissue residues of 2,4-DCP in sheep liver and kidney were slightly higher (0.16 and 0.26 mg/kg tissue, respectively) but dropped to 0.15 and 0.07 mg/kg tissue, respectively, seven days after withdrawal of the herbicide from the diet.

5.2.3 Animal Studies

5.2.3.1 Carcinogenesis

Little information is available on the carcinogenicity of the three chlorinated phenols under evaluation. Only the trichlorinated 2,4,6-TCP has been tested by the oral route (Innes *et al*. 1969, NCI 1979).

Innes and coworkers (1969) administered 100 mg 2,4,6-TCP/kg by gavage to two strains of hybrid mice (C57BL/6 x C3H/Anf and C57BL/6 x AKR) for three weeks beginning when the mice were seven days old, followed by 260 mg/kg diet for 18 months. This resulted in an estimated exposure of 20-25 mg/kg of 2,4,6-TCP. Elevated incidences of reticulum-cell sarcomas and hepatomas were reported but data were not provided.

The National Cancer Institute (1979) has recently completed an assessment of the carcinogenicity of 2,4,6-TCP in F344 rats and B6C3F1 mice. In rats, groups of 50 animals of each sex were given 5,000 or 10,000 mg 2,4,6-TCP/kg diet for 106 to 107 weeks; 20 rats of each sex served as controls. Dose-related reductions in mean body weights of treated males and females compared to controls were noted throughout the study. Statistically significant dose-related incidences of lymphomas or leukemias were noted in male rats (See Table 5-1). Treated female rats did not exhibit lymphomas or monocytic leukemia at a significant incidence. Leukocytosis and monocytosis of peripheral blood and hyperplasia of the bone marrow were present, however, in treated female rats and male rats not exhibiting lymphoma or leukemia.

In a separate experiment with B6C3F1 mice, 50 male mice were given 5,000 or 10,000 mg 2,4,6-TCP/kg diet for 38 weeks. The dietary concentration was subsequently reduced to 2,500 and 5,000 mg/kg diet respectively, due to excessively low body weights in females. This reduced dietary

TABLE 5-1. INCIDENCE OF NEOPLASMS IN F344 RATS FED 2,4,6, - TRICHLOROPHENOL IN THE DIET FOR TWO YEARS

Treatment Group (mg/kg diet)	Malignant Lymphoma	Leukemia	Bone Marrow Hyperplasia	Leukocytosis
Males:				
0	1/20 (5%)	3/20 (15%)	0/20 (0%)	0/20 (0%)
5,000	2/50 (4%)	23/50 (46%)	26/50 (52%)	13/50 (26%)
10,000	0/50 (0%)	29/50 (58%)	15/50 (30%)	11/50 (22%)
Females:				
0	0/20 (0%)	3/20 (15%)	0/20 (0%)	0/20 (0%)
5,000	0/50 (0%)	11/50 (22%)	16/50 (32%)	6/50 (12%)
10,000	2/50 (4%)	11/50 (22%)	2/50 (4%)	3/50 (6%)

Source: Adapted from NCI (1979)

concentration was maintained for the remaining 67 weeks of the study. The time-weighted average doses were 5,214 and 10,428 mg/kg diet, respectively. Statistically significant incidences ($p < 0.001$) of hepatocellular carcinomas or adenomas were recorded in all groups of mice treated with 2,4,6-TCP (see Table 5-2).

No data are available on the potential carcinogenicity of 2-CP or 2,4-DCP by the oral route. However, both of these compounds, as well as 2,4,6-TCP, have been evaluated for their tumor-promoting activity in a series of experiments by Boutwell and Bosch (1959). Female Sutter mice were initiated with a single dermal application of 0.3% dimethylbenzanthracene (in benzene) to the back, followed by repetitive, twice-weekly applications of ∿25 μl of a 20% solution of either 2-CP, 2,4-DCP, or 2,4,6-TCP to the same area for 15 weeks. The results of these experiments are presented in Table 5-3; related promoter experiments with phenol are included for comparative purposes. The promoting activities of 2-CP and 2,4-DCP appear comparable to phenol; however, no statistical evaluation or dose-response data were presented. The trisubstituted 2,4,6-TCP was inactive. As with phenol, the promoting activities of 2-CP and 2,4-DCP are probably associated with their irritancy and subsequent skin hyperplasia and are thus not appropriate for assessment of human risk by ingestion.

In a separate experiment, Boutwell and Bosch (1959) treated female Sutter mice with 20% 2-CP in dioxane twice weekly for 12 weeks without prior initiation. Forty-six percent of the survivors at 12 weeks had developed papillomas but no epithelial carcinomas were found.

In summation, dietary administration of 2,4,6-TCP is carcinogenic in male F344 rats, inducing lymphomas or leukemias. This compound is also carcinogenic in both sexes of B6C3F1 mice, inducing hepatocellular carcinomas or adenomas. The carcinogenic potentials of 2-CP and 2,4-DCP have not been tested by the oral route, but both compounds do appear to possess tumor-promoting activities in mice, probably a result of an irritant response. The trisubstituted 2,4,6-TCP is inactive in this respect.

5.2.3.2 Mutagenesis

Chung (1978) noted a fivefold increase in chromatid deletions (12% vs. 2% in controls) in bone marrow cells of Sprague-Dawley rats orally administered 130 mg/kg 2-CP every other day for one week. Complete inhibition of mitosis was noted in bone marrow cells taken from similarly treated rats after exposures of two to three weeks.

Fahrig and associates (1978) reported a weak but significant increase ($p < 0.02$) in forward mutations in the yeast, Saccharomyces cerevisiae MP-1 following exposure to 400 mg/l 2,4,6-TCP for 3.5 hours. Mutants numbered 10.29 colonies in 2,4,6-TCP-treated cells compared to 5.63 colonies for control cultures. No positive control agents were tested, making evaluation of the significance of the results with 2,4,6-TCP difficult to adequately assess.

TABLE 5-2. INCIDENCE OF NEOPLASMS IN B6C3F1 MICE FED 2,4,6, -TRICHLOROPHENOL IN THE DIET FOR TWO YEARS

Treatment Group (mg/kg diet)	Hepatocellular Carcinoma	Hepatocellular Adenoma	Hepatocellular Hyperplasia
Males:			
0	1/20 (5%)	3/20 (15%)	2/20 (10%)
5,000	10/49 (20%)	22/49 (45%)	12/49 (24%)
10,000	7/47 (15%)	32/47 (68%)	6/47 (13%)
Females:			
0	0/20 (0%)	1/20 (5%)	1/20 (5%)
5,214[a]	0/50 (0%)	12/50 (24%)	1/50 (2%)
10,428[a]	7/48 (14%)	17/48 (35%)	6/48 (13%)

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[a] Time-weighted average dose.

Source: Adapted from NCI (1979)

TABLE 5-3. INCIDENCE OF TUMORS IN SUTTER MICE INITIATED WITH 0.3% DIMETHYLBENZANTHRACENE AND TREATED WITH VARIOUS SUBSTITUTED PHENOLS

Promoter (applied two times per week)	Duration of Treatment (week)	Incidence of Papillomas (% of survivors)	Incidence of Epithelial Carcinoma (%)
(20% soln. in benzene)			
None	15	1/15 (7%)	0%
2 - Chlorophenol	15	19/31 (16%)	10%
2,4 - Dichlorophenol	15	13/27 (48%)	11%
2,4,6 - Trichlorophenol	15	0/26 (0%)	0%
Phenol	12	14/22 (64%)	0%
Benzene (control)	24	3/27 (11%)	0%
2,4 - Dichlorophenol	24	12/16 (75%)	6%
Phenol	24	18/20 (90%)	15%

Source: Adapted from Boutwell and Bosch (1959)

In another study, Rasanen and coworkers (1977) tested both 2,4-DCP and 2,4,6-TCP in the Ames Salmonella microsomal test at concentrations of 0.5, 5, 50, and 500 μg/plate. Both compounds were evaluated in the presence and absence of liver microsomal activation in strains TA98 and TA1537 (frame-shift mutants) and strains TA100 and TA1535 (base-pair mutants) of *Salmonella typhimurium*. Some toxicity was evident at the highest concentration, but no increase in mutations above background values was seen.

Antimitotic and antimeiotic effects (e.g., chromosome stickiness, lagging chromosomes, fragmentation) have also been noted in vetch (*Vicia faba*) exposed to 2,4-DCP (Amer and Ali 1974) and in pea plants (*Pisum sativum* var. Alaska) exposed to either 2,4-DCP (3.07 x 10^{-4}M)or 2,4,6-TCP (0.51 x 10^{-4}M) (Nethery and Wilson 1966). The relationship of these changes to alterations in mammalian cells, however, has not been established.

In summary, therefore, 2-CP exhibits mutagenic activity in mice, but available data on 2,4-DCP and 2,4,6-TCP are insufficient to draw any conclusions on the mutagenic potential of these chlorinated phenols.

5.2.3.3 Adverse Reproductive Effects

There are no data available on the effects of 2-CP), 2,4-DCP, or 2,4,6-TCP on the developing embryo or the reproductive process.

5.2.3.4 Other Toxicological Effects

Toxicological data on 2-CP, 2,4-DCP, and 2,4,6-TCP are limited, but the data that are available suggest a similarity to the effects noted with phenol. The median acute lethal dose of 2-CP or 2,4,6-TCP is within a 100-to-950-mg/kg dose range, while 2,4-DCP appears to be somewhat less toxic (see Table 5-4). By comparison, the median acute lethal dose for phenol falls into the 180-to-600-mg/kg range, regardless of species or route of administration (RTECS 1978).

The signs of acute toxicity for chlorinated phenols are similar to phenol in both rats and mice. Following a lethal dose, a brief period of excitation and increased respiratory rate occurs, followed by clonic convulsions and/or motor weakness (hypotonia), dyspnea, coma, and, finally, death. Differences in the onset of symptoms following doses of each of the chlorinated phenols have been attributed to the number of chlorine substituents. Increasing the number of chlorine substituents also appears to reduce convulsant activity (Farquharson *et al*. 1958). The reasons for these variations may stem from absorption and distribution-rate differences.

The convulsant activity of various chlorinated phenols was described by Farquharson and coworkers (1958). At sublethal doses, convulsions occur in rats within one minute after intraperitoneal injection and are

TABLE 5-4. ACUTE LETHAL VALUES FOR CHLOROPHENOLS IN MAMMALIAN SPECIES

Compound	Route	Species	LD_{50} (mg/kg)	Reference
2-Chlorophenol	Oral	Rat	670	RTECS (1978)
		Mouse	670	RTECS (1978)
	Subcutaneous	Rat	950	RTECS (1978)
		Rabbit	950 LDLo[a]	RTECS (1978)
		Guinea Pig	800 LDLo	RTECS (1978)
	Intraperitoneal	Rat	230	Farquharson *et al*. (1958)
	Intravenous	Rabbit	120 LDLo	RTECS (1978)
2,4-Dichlorophenol	Oral	Rat	4,000	Kobayashi *et al*. (1972)
			2,830	Vernot *et al*. (1977)
			580	RTECS (1978)
		Mouse	1,630	Vernot *et al*. (1977)
			1,600	Kobayashi *et al*. (1972)
	Subcutaneous	Rat	1,730[b]	RTECS (1978)
	Intraperitoneal	Rat	430	Farquharson *et al*. (1958)
2,4,6-Trichlorophenol	Oral	Rat	820	RTECS (1978)
		Human	500 LDLo	RTECS (1978)
	Intraperi-	Rat	276	Farquharson *et al*. (1958)

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[a] Lowest reported lethal dose.

[b] Fuel oil was used as the vehicle in this experiment and may have enhanced rapid uptake of 2,4-dichlorophenol.

characterized by the appearance of generalized tremors, sometimes starting in the neck and forepaws, and increasing in severity to intermittent convulsions and loss of righting reflex. Hypotonia was also observed, progressing to the point of complete prostration. With 2,4-DCP, auditory or mechanical stimuli elicited muscle twitches during hypotonia (Farquharson et al. 1958). Angel and Rogers (1972) described similar manifestations in mice with 2-chlorophenol.

Farquharson and associates (1958) noted acute exposure to chlorophenols with pk values of 7.85 or less appear to be associated with marked hypotonia, increase in body temperature, and early onset of rigor mortis following death--effects not uncommon to oxidative uncouplers. Limited in vitro studies indicate that 2-CP, 2,4-DCP, and 2,4,6-TCP do indeed inhibit oxidative phosphorylation (i.e., inhibit production of ATP) in rat liver mitochondria (Farquharson et al. 1958, Mitsuda et al. 1963). Mitsuda and coworkers (1963) reported that the I_{50} (the concentration at which ATP production is approximately halved) decreased in the order of phenol (5000 μM), 2-CP (520 μM), 2,4-DCP (42 μM), and 2,4,6-TCP (18 μM).

Relatively few long-term studies are available on 2-CP, 2,4-DCP, and 2,4,6-TCP. Chung (1978) treated rats orally every other day for three weeks with 65 or 130 mg/kg of 2-chlorophenol dissolved in olive oil. Weight gain was significantly reduced in both treatment groups, and,notably, liver weight was increased in treated animals. Hemoglobin levels and hematocrit values were significantly depressed by the third week. but there were no significant effects on total serum protein or serum albumin. Serum alkaline phosphatase (Alk. Phos.) and serum lactic dehydrogenase (LDH) activities were initially increased after one week, but by three weeks Alk. Phos. had dropped below baseline, while LDH had returned to control values. Serum glutamate-oxaloacetate transaminase (GOT) activity was significanlty elevated after one week of treatment. Liver function was also signficantly altered by 2-chlorophenol. Mitochondrial respiration in vivo and in vitro was depressed; microsomal cytochrome P-450 was depressed as were liver LDH and GOT activities. Histologically, liver tissue was degenerated with congestion, atrophy, swelling, vacuolation, dilation of rough endoplasmic reticulum and mitochondrial swelling and destruction of mitochondrial cristae.

Kobayashi and coworkers (1972) studied the effects of 2,4-dichlorophenol in mice fed the compound in the diet for six months. Based on food consumption data, the dosages in the 4 treatment groups were approximately 17, 45, 100, and 230 mg/kg /day. Growth rate was slightly depressed at the 45- and 100-mg/kg levels and significantly depressed in the 230-mg/kg group, particularly early in the study (3 to 13 weeks). Food consumption of the treatment groups compared with the control group was essentially unaffected. Liver- and kidney-to-body-weight ratios were somewhat depressed in treated mice compared to those in the controls, but a dose-effect relationship was not clearly evident. Erythrocyte and leucocyte counts were similar in all groups as were serum glutamicoxalacetic transaminase (GOT) and glutamic-pyruvic transaminase (GPT) levels.

The histological appearance of heart and kidneys was also similar. A slight increase in incidence of histologic abnormalities of the liver, such as "small round-cell infiltration", "swelling of hepatic cells", and "unequal size of hepatic cells", was noted in the highest treatment group when compared to controls.

In another study, Miura and coworkers (1978) examined the ability of orally administered 2,4-DCP to induce hepatic porphyria in rats. In one experiment, the dosage of 2,4-DCP was 250 mg/kg/day the first week, 340 mg/kg/day the second week, 1,000 mg/kg/day for the first 4 days of the third week, and finally 550 mg/kg/day for the first three days of the fourth week. Urinary excretion of γ aminolaevulinic acid and coproporphyrin was slightly deceased by the treatment with 2,4-DCP, but urinary porphobilinogen and fecal porphyrin showed no significant increase compared to controls. Accumulation of porphyrins in the liver and kidneys was normal. In a second experiment, rats were given 30 to 70 mg/kg/day of 2,4-DCP in the diet for 17 weeks. As in the first experiment, there were no significant changes in excretion of porphyrins and related compounds. A slightly reduced growth rate and slight histologic changes in the liver were noted in the treated rats compared to controls. The livers of 3/5 treated rats showed vacuolar degeneration, 5/5 had intralobular leucocytic infiltration, and 3/5 displayed leucocytic infiltration of the perivascular fibrous capsule.

No adverse effects were noted in either F344 rats fed up to 14,700 mg 2,4,6-TCP/kg diet or B6C3F1 mice given up to 21,000 mg/kg diet for 7 weeks. Reduced survival was observed in male rats fed 21,500 mg/kg diet and in female rats and both sexes of mice at a dietary exposure of 31,500 mg/kg diet. Histopathological changes were noted only in rats fed the 46,000 mg TCP/kg diet. These changes consisted of moderate to marked increase in splenic hematopoiesis in both males and females and midzonal vacuolation of hepatocytes in 2/5 males. No abnormal histopathology was seen in mice fed 31,500 mg TCP/kg diet for 7 weeks (NCI 1979).

5.2.4 Human Studies

Aside from a single report of an oral lethal dose of 500 mg/kg for 2,4,6-TCP (RTECS 1978), there are no data on the effects of 2-CP, 2,4-DCP, or 2,4-6-TCP in humans. The acute toxicity of chlorophenols to humans on a mg/kg basis, however, would appear to be comparable to that in animals.

It is difficult to estimate subchronic and chronic toxicity of 2-CP, 2,4-DCP, and 2,4,6-TCP in humans since there is no available information on human exposure and the experimental data in animals for these compounds are minimal or non-existent.

Hardell (1979) notes an apparent association between human exposure to phenoxyacetic acid or chlorophenols and malignant lymphoma of the histiocytic type. The correlation to chlorophenols is uncertain and one must also take into consideration the effect of exposure to impurities such as dibenzodioxins and dibenzofurans that contaminate commercial chlorophenol preparations.

5.3 HUMAN EXPOSURE

5.3.1 Introduction

It is apparent that data on chlorophenols is lacking in many areas, including monitoring, fate,and toxicity. Thus, there is little basis for estimating exposure of human receptors to these compounds. However, the releases of 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol to the environment are limited, thus reducing the potential for exposure. Recent reviews of the subject by the EPA (1980a, 1980b, 1980c) and Kozak and coworkers (1979) concluded that there was little likelihood of widespread human exposure to these compounds.

This section will examine the limited data available in an attempt to define exposure further. It should be noted that limited data make such estimates quite tentative and that it is difficult to associate subpopulations with exposures.

5.3.2 Ingestion

5.3.2.1 Drinking Water

Sources of chlorophenols to ambient waters and potentially to drinking water supplies include chemical manufacturers' discharges, wastewater chlorination, and agricultural runoff. Land application of the herbicide 2,4-D could potentially result in the contamination of groundwater wells used for drinking water. There is also a potential for formation of chlorophenols in the chlorination of drinking water supplies (see Chapter 3.0).

The only information available on chlorophenol levels in finished drinking water is for 2.4-dichlorophenol. The compound was detected in 56 out of 108 samples at a mean level of 0.18 μg/l (for positive values) (U.S. EPA 1978). Assuming a two-liter daily consumption of drinking water, a daily exposure level of approximately 0.4 μg of 2,4-dichlorophenol can be estimated.

According to ambient surface water data for all three chlorophenols, also a limited data base, concentrations are usually less than 50.0 μg/l.[1] A maximum daily amount of 60 to 100 μg can be estimated for exposure through drinking untreated water contaminated with any of the chlorophenols. This estimate should be considered an upper limit and is probably applicable to a very small subpopulation. An exposure of 0.4 μg/day may be more common, at least for 2,4-DCP.

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[1] The majority of these data are remarked as either at or below the reported level, which is a detection limit, therefore the actual concentrations present are overestimated.

Spills can result in localized contamination of surface or groundwater, as described in Chapter 4.0. These types of incidents have the potential for resulting in higher exposures than those discussed above. However, based on the conclusions of Chapter 4.0, the chlorophenols, especially the mono- and dichlorophenols, are readily biodegradable in surface waters following an initial period of microbial population acclimation. Therefore for chloro- and dichlorphenol spills in aerated, biologically active surface waters, high concentrations are likely to be short term. Spills of trichlorophenol and of all three chlorophenols under reduced conditions (i.e., into groundwater) may be more persistent and present a long-term potential for exposure.

A characteristic of phenols in general which would tend to decrease the likelihood of human exposure to high concentrations is the compounds' low odor thresholds in water. The two EPA Water Quality Criteria proposed for some chlorophenol compounds reflect this (U.S. EPA 1980a,b,c). The human health criterion based on odor characteristics is four orders of magnitude below the criterion based on available toxicity data for 2,4-dichlorophenol.

5.3.2.2 Food

Ingestion of chlorinated phenols in food has not been documented (Kozak et al. 1978, U.S. EPA 1979). However, as was discussed in Chapter 4.0, their presence in food is possible, especially 2,4-dichlorophenol. This compound has been reported in plants as a result of application of the herbicide 2,4-D. The presence of 2,4-DCP in plants may be a result of plant metabolism of 2,4-D or uptake of the herbicide from soil. Although the possibility of these residues persisting to consumption exists, the exposures can not be approximated without residue data for food crops.

Chapter 4.0 also reports tissue residue levels and bioconcentration factors (BCFs) in fish for the three compounds. Based on U.S. EPA estimated BCFs for the chlorophenols in the edible portion of fish, tissue levels are 4.0 mg/kg, 1.2 mg/kg, and 4.5 mg/kg for 2-CP, 2,4-DCP, and 2,4,6-TCP, respectively assuming ambient water levels of 10 μg/l (U.S. EPA 1980a, 1980b, 1980c). Assuming an average fish consumption of 21 g/day (USDA 1979), intakes of 27, 9 and 32 μg/day can be estimated for the respective chlorophenols. Maximum intakes, based on water concentrations of 60 μg/l for 2-CP and 30 μg/l for 2,4-DCP and 2,4,6-TCP, are estimated to be 137, 26 and 95 μg/day, respectively. However, actual residues of these compounds in aquatic organisms are limited to reports of 2 mg/kg (bluegill) and 18 mg/kg (trout) for 2-CP and 2,4-DCP, respectively. These limited data suggest that the theoretically derived bioconcentration provides an upper limit measure of uptake. although more data are required to confirm this. Metabolic data indicate that fish may rapidly metabolize and excrete the chlorophenols so that significant levels of accumulation are not achieved.

The contamination of livestock by 2,4-DCP through the ingestion of crops treated with herbicides was estimated by the U.S. EPA (1980b). A worst case estimate was made assuming a dosing of 2,4-DCP of 7 mg/kg body weight for cattle. The levels of 2,4-DCP accumulating in liver and kidney were estimated at 0.11 µg/g and 0.56 µg/g, respectively. Assuming ingestion of 0.5 kg of kidney daily for humans, an exposure of 280 µg/g of 2,4-DCP was estimated. This level is a worst case example because it assumes a constant diet for cattle of 2,4-D sprayed foliage only and no metabolism of the substance.

Dairy cattle dosed with high levels of 2,4-DCP were not found to accumulate the compound in their milk (U.S. EPA 1980b). Therefore, ingestion of milk is not considered to be a significant exposure route for 2,4-DCP.

5.3.3 Inhalation

There is a potential for exposure of humans to airborne levels of chlorophenols, most significantly during the use of products containing these compounds. In addition, di- and trichlorophenols were identified in the gas condensates from municipal incinerators (Olie et al. 1977); unfortunately, however, levels were not quantified. There was no information on ambient atmospheric levels of any of the chlorophenols. All three compounds are fairly volatile but little is known about their persistence or ultimate fate in the troposhere (Chapter 4.0).

The only air monitoring data available for any of the chlorophenols reported 2-chlorophenol concentrations in the immediate vicinity of a train derailment spill of the compound (APHA 1979). Concentrations on the day of the spill measured 0.02 mg/m^3 to 0.7 mg/m^3 (0.004-0.19 ppm). Eighteen days following the spill, air levels were reduced to <2 µg/m^3 (<0.0005 ppm). Urine levels in the clean-up workers measured 1.98 mg/l approximately 2 months following the spill; however the pathways, duration, and time of exposure were not given, so the exposure levels cannot be estimated. The urine levels were not detectable (detection limit 0.25 mg/l) by the following month. People living within 40-200 feet of the spill area who were expected to be exposed solely via inhalation had no detectable levels in their urine 3 months after the spill. No earlier sampling was done for acute exposure levels.

A small subpopulation may be exposed to 2,4,6-trichlorophenol through the use of derivative products such as fungicides used for preserving wood, leather, and glue. This exposure is expected to be primarily occupational during the process of chemical treatment. Exposure levels could not be quantified since the chemical composition and application rates of these compounds are unknown. There may be exposure to volatilization of 2,4-dichlorophenol during application of the widely used herbicide 2,4-D; however, no specific information regarding this exposure was available.

5.3.4 Dermal Absorption

Due to their lipid-solubility and low degree of ionization at typical biological pH, the chlorophenols are theoretically expected to be absorbed through intact skin (Farquharson et al. 1958). The only information available on absorption of chlorophenols indicated that 2,4,6-trichlorophenol in a 0.09% solution permeated a human epidermal membrane *in vitro* without causing harm (Roberts *et al*. 1977). No other data were provided.

Dermal absorption of chlorophenols from either surface or municipal water supplies is expected to be minimal due to the low concentrations (<50 µg/l) usually detected (see Section 5.3.2.1). Exposure to higher concentrations would be expected in occupational settings such as at chemical production plants, textile and leather process plants, and in certain wood preserving operations.

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6.0. EFFECTS AND EXPOSURE--AQUATIC BIOTA

6.1 SUMMARY

The lowest concentration of 2-chlorophenol (2-CP) at which toxic effects have been reported in a freshwater organism was 2.58 mg/l, a 48-hour LC_{50} for *Daphnia magna* (water flea). The lowest reported LC_{50} for a vertebrate to 2-CP was 6.6 mg/l for the bluegill. The compound 2,4-dichlorophenol (2,4-DCP) appears somewhat more toxic to the bluegill, with the only LC_{50} reported at 2.02 mg/l. For the compound 2,4,6-trichlorophenol (2,4,6-TCP) the LC_{50} for bluegill was substantially lower, 0.32 mg/l. LC_{50} values for *Daphnia magna* did not vary significantly among the three compounds. Chronic levels for *Pimephales promelas* (fathead minnow) were reported at >3.9 mg/l, 0.37 mg/l. and 0.72 mg/l for 2-CP, 2,4-DCP and 2,4,6-TCP, respectively.

The alga *Chlorella pyrenoidosa* was apparently much more sensitive than either fish or daphnids to variations in the degree of chlorination in the phenol with successive increases in phenol chlorine content. The duckweed was approximately ten times as sensitive to 2,4,6-TCP as to 2,4-DCP. Since toxicity values for pentachlorophenol are generally in the 0.01 to 1.0 mg/l range, it appears that toxicity generally increased for all aquatic species with increasing chlorination of phenol.

One study found that water hardness had no effect on the toxicity of 2-CP to fathead minnows, but other species and the other chlorinated phenols remain to be tested. It has been hypothesized that the toxicity of a substituted phenol increases as the pH of the solution approaches the pKa (dissociation constant) value of the phenolic compound. However, this parameter has not been tested using any of the three chlorinated phenols.

Very limited information was available concerning the exposure of aquatic life to chlorophenols in the environment. The monitoring data for all three chlorophenols in ambient surface waters are, for the most part, at or below analytical detection limits, usually less than 0.01 mg/l. A few observations were between 0.01 and 0.1 mg/l. At least three fish kills have been attributed to chlorophenols accidently released from chemical plants and a cooling tower. Therefore, occasionally aquatic life are exposed to much higher concentrations than the monitoring data indicate.

6.2 EFFECTS ON AQUATIC BIOTA

6.2.1 Introduction

This section provides laboratory information about the levels of 2-CP, 2,4-DCP, and 2,4,6-TCP at which the normal behavior and metabolic processes of aquatic organisms are disrupted. Limited data were available representing only a few aquatic species.

Most of the available data were derived from static bioassays, which are usually less reliable than continuous-flow experiments because there is less control of toxicant concentrations. This is especially important for the relatively volatile chlorophenols which undergo a decrease in concentration due to volatilization over the course of a toxicity experiment.

No information on the toxicity of chlorinated phenols to terrestrial organisms was available.

6.2.2 Freshwater Organisms

6.2.2.1 Chronic and Sublethal Effects

Low levels of toxicants which remain for extended periods are generally considered to represent "normally" polluted conditions in natural waterways. Under these circumstances, aquatic biota may become acclimated to the pollutant, or they may exhibit certain behavioral or physiological symptoms. Prolonged exposure even to low concentrations of chlorinated phenols could ultimately result in mortality. Even if fish are not killed by long-term exposure to these toxicants, the survival of local populations may be endangered.

The chronic values for fathead minnows (*Pimephales promelas*) for 2-CP, 2,4-DCP, 2,4,6-TCP, as determined by U.S. EPA (1980a,1980b,1980c) are >3.9 mg/l, 0.37 mg/l, and 0.72 mg/l, respectively. In eight-day chronic bioassays with fathead minnows, Phipps *et al*. (manuscript) determined LC_{50} values of 6.34 mg/l and 6.5 mg/l for 2-CP and 2,4-DCP, respectively. In static bioassays conducted by Applegate *et al*. (1957), bluegill sunfish (*Lepomis macrochirus*) and sea lamprey larvae (*Petromyzon marinus*) were exposed to 5.0 mg/l 2,4-DCP. Both species became "ill," in 0.5 hour and 1 hour, respectively.

Telford (1974) reported increased glucose levels in the blood of three species of crayfish (*Oronectes propinquus*, *O. immunis*, and *Cambarus robustus*) after 10 days of exposure to 1.0 mg/l 2,4-DCP. A 14% mortality was also observed during this period.

6.2.2.2 Acute Effects

Acute toxicity is defined as toxicant-induced mortality over a short period of time, generally within 96 hours. Although fish in natural waterways are more likely to be exposed to lower concentrations which may produce chronic or sublethal effects, industrial discharges and spills can temporarily result in levels high enough to cause fish kills (see Section 6.3.3 of this chapter).

A summary of reported LC_{50} values in short-term toxicity tests with the three chlorinated phenols is given in Table 6-1. The lowest LC_{50} derived for 2,4,6- TCP (0.32 mg/l) is considerably lower than the lowest LC_{50} values given for 2-CP and 2,4-DCP (6.6 mg/l and 2.02 mg/l, respectively).

Other acute toxicity information on freshwater finfish reported lethal effects levels in approximately the same range as the data in Table 6-1. Goldfish (Carassius auratus) exposed to 31.1 mg/l 2-CP exhibited 42% mortality in 8 hours (Gersdorff and Smith 1940). In two separate experiments, Applegate et al. (1957) reported death in rainbow trout (Salmo gairdneri) after 3 hours and 6 hours in 5.0 mg/l 2,4-DCP. Bluegill and larval sea lamprey also had a lethal response to this concentration of 2,4-DCP in 12 hours (Applegate et al. 1957).

The only invertebrate for which LC_{50} data were available was Daphnia magna (see Table 6-1). The effects levels are similar for all three compounds. Telford (1974) observed 100% mortality in three species of crayfish in 48-hour and 7-day bioassays at 10.0 mg/l and 5.0 mg/l 2,4-DCP, respectively. Two Lymnaeid snails, Pseudosuccinea collumnella and Fossaria cubensis, exposed to 2,4-DCP and 2,4,6-TCP had associated 24-hour LC_{50}s of 10.0 mg/l and 5.0 mg/l, respectively (Batte and Swanson 1952).

6.2.2.3 Effects on Plants

All of the available information on the effects of the three chlorinated phenols on algae was found in Huang and Gloyna (1968), who studied Chorella pyrenoidosa. A reduction in chlorophyll mass resulted from 72 hours of exposure to 400 mg/l 2-CP. In experiments with 2,4-DCP, a 56.4% reduction in photosynthetic oxygen production occurred in 50.0 mg/l; 100 mg/l caused complete destruction of chlorophyll. The LC_{50} for chlorosis in 72-hour experiment with 2,4,6-TCP was 10.0 mg/l. No effects were observed for 2-CP, 2,4-DCP, and 2 4,6-TCP at concentrations of 10.0 mg/l, 1.0 mg/l, and 1.0 mg/l, respectively. A 50% reduction in chlorophyll content for duckweed (Lemna minor) was observed in 58.32 mg/l 2,4-DCP, and in 5.923 mg/l 2,4,6-TCP (Blackman et al. 1955).

6.2.3 Marine Organisms

Only one study was found which dealt with the toxic effects of any of the three chlorinated phenols on marine organisms. In an acute bioassay of unspecified duration, Hiatt et al. (1953) observed a "moderate reaction" by the Hawaiian mountain bass (Kuhlia sandricensis) to 20.0 mg/l 2,4-DCP.

6.2.4 Factors Affecting the Toxicity of Chlorinated Phenols

Of the many parameters that are controlled in toxicity bioassays, only water hardness has been tested for its effects on the toxicity of

TABLE 6-1. ACUTE TOXICITY (LC_{50}) OF CHLORINATED PHENOLS TO AQUATIC ANIMALS

Range of Concentrations (mg/l)	Species	Compound
	Fish	
6.6-10.0	Bluegill (*Lepomis macrochirus*)	2-Chlorophenol
11.6-14.5	Fathead minnow (*Pimephales promelas*)	2-Chlorophenol
12.3	Goldfish (*Carassius auratus*)	2-Chlorophenol
20.2	Guppy (*Poecilia reticulatus*)	2-Chlorophenol
58.0[a]	"Minnows"	2-Chlorophenol
2.02	Bluegill (*Lepomis macrochirus*)	2,4-Dichlorophenol
8.23	Fathead minnow (*Pimephales promelas*)	2,4-Dichlorophenol
0.32	Bluegill (*Lepomis macrochirus*)	2,4,6-Trichlorophenol
0.6-9.04	Fathead minnow (*Pimephales promelas*)	2,4,6-Trichlorophenol
	Invertebrates	
2.58-7.43	*Daphnia magna*	2-Chlorophenol
2.60-11.0[b]	*Daphnia magna*	2,4-Dichlorophenol
6.04	*Daphnia magna*	2,4,6-Trichlorophenol

---

[a] Ingols and Gaffney (1966).

[b] Bringmann and Kuhn (1977).

Source: Data compiled from EPA (1980a, 1980b, 1980c), unless otherwise noted.

the three chlorinated phenols. Pickering and Henderson (1966) exposed fathead minnows to 2-CP in 24-hour, 48-hour, and 96-hour acute tests in either soft water (20 mg/l hardness) or hard water (360 mg/l hardness). The resultant LC_{50}s revealed no significant differences in sensitivity to the two test solutions.

Blackman et al. (1955) have hypothesized that the toxicity of a substituted phenol increases as the pH of the solution approaches the pKa value of the phenolic compound. If this were true, the toxicity of 2-CP, 2,4-DCP, and 2,4,6-TCP would be greatest at pHs of 8.4, 7.4, and 6.0, respectively. However, this is a theoretical conclusion, and remains to be corroborated by experimentation with specific compounds over a selected pH range.

6.2.5 Water Quality Criteria

The U.S. Environmental Protection Agency's Division of Water Quality Criteria and Standards has not proposed specific criteria for any of the chlorinated phenols for the protection of aquatic life due to lack of sufficient data (U.S. EPA 1980a, U.S. EPA 1980b, U.S. EPA 1980c). The lowest effects levels reported in the support document are the same as those described in the preceeding section.

6.3 EXPOSURE TO AQUATIC BIOTA

6.3.1 Introduction

Information on the levels of chlorophenols in the aquatic environment is extremely limited. The monitoring data from most regions in the United States are so scarce that any generalizations would be unreliable. There are a few instances of fish kills caused by the release of chlorophenols into natural water bodies, indicating that chlorophenols do occasionally appear at levels harmful to aquatic life. No data on terrestrial exposure were available; however, some exposure would be expected to be associated with the 2,4-dichlorophenol present as an impurity and degradation product of the widely used herbicide 2,4-D.

6.3.2 Monitoring Data

The data provided by STORET (U.S. EPA 1979a) on chlorophenol levels in ambient waters of major U.S. river basins during 1977-1979 amount to barely 300 observations, indicating that these chemicals are monitored infrequently (see Section 4.4). The only regions in which more than ten measurements for any of the phenols were reported were Lake Michigan, the Missouri River basin, and the Pacific Northwest. For 2-CP, 2,4-DCP, and 2,4,6-TCP, the Pacific Northwest appears to have the highest concentrations, with 108 (71%) of the 153 observations in the 10.1-100 μg/l category. For the United States excluding the Pacific Northwest, a large majority of the measurements are between 1.1 μg/l and 10.0 μg/l for the three phenolics, while only 4-8% are between 10.1 μg/l and 100 μg/l. It should be noted that virtually all available data are either at or below the level of detection, indicating that the concentration distribution represented tends to overestimate the concentrations actually present in the samples.

6.3.3 Exposure to Industrial Effluents

Concentrations of chlorophenols in industrial effluents have been reported in excess of ambient levels (see Tables 3-5 and 4-6). Industries with relatively high average effluent concentrations of 2,4-dichlorophenol include timber finishing plants (84 mg/l), timber barking plants (3.2 mg/l), leather tanners (1.1 mg/l) and pesticide producers (73.2 mg/l in wastewater). High concentrations of 2,4,6-trichlorophenol are discharged by the timber industry (up to 3 mg/l), paint and ink plants (2.4 μg/l) and pesticide producers (up to 2.8 mg/l in wastewater). Information on 2-dichlorophenol is much more limited; one pesticide plant had a concentration of 2.8 mg/l in wastewater.

These data suggest that aquatic life in the vicinity of effluent pipes may be exposed to chlorophenol concentrations significantly higher than those reported in STORET. As reviewed in Chapter 4.0, the available concentration would be reduced by dilution in the receiving waters, adsorption onto sediment and volatilization to the atmosphere, especially in aerated waters. Biodegradation may reduce concentrations of 2-chlorophenol and 2,4-dichlorophenol significantly within one to two weeks in the presence of acclimated active microbial populations.

6.3.4 Fish Kill Data

Table 6-2 provides information on the location of and activities associated with fish kills attributed to chlorophenols between 1971 and 1974. Unfortunately, no data on aqueous concentrations were given in the reports nor were other toxic substances present in the spill (e.g. pentachlorophenol) always identified. It is impossible to speculate upon the most frequent sources of chlorophenol emissions on the basis of such limited evidence. However, since chlorophenols are used primarily by chemical plants, it is likely that spills and discharges will occur more frequently in areas which are densely industrialized than in rural areas. In addition, spills associated with releases from chlorophenol-treated industrial cooling waters would have a similar national distribution.

TABLE 6-2. DATA ON FISH KILLS ATTRIBUTED TO CHLORINATED PHENOLS (1971-1974)

Year	Water Body	Location	Duration	Number Killed	Cause
1971	Allen Creek	Rochester, NY	2 days	2,000	Possibly chlorinated phenols from air cond. system in cooling tower.
1973	Anderson Creek	Anderson, CA	34 days	700	Wood preserv. storage tanks discharge of "polychlorinated phenols and phenates" to sawmill waste collection system, then to Anderson Creek
1974	Fourmile Creek and tributaries	Model City, NY	3 days	Severe	Break in 2,4-DCP holding dike

Source: U.S. EPA (1979b).

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7.0 RISK CONSIDERATIONS

7.1 INTRODUCTION

The purpose of this chapter is to evaluate the potential risks to humans and aquatic biota resulting from exposure to environmental concentrations of chlorophenols. The analysis of risk is reduced by a limited data base regarding the health effects of mono- and dichlorophenol and environmental monitoring data for all three chlorophenols which permit no more than very general estimates of exposure levels. In this chapter the two lesser chlorinated phenols are discussed separately from 2,4,6-trichlorophenol because the lack of dose-response data for the two compounds necessitates different treatment in the estimation of risk.

7.2 HUMANS

7.2.1 Statement of Risk

A quantitative estimate of human risk resulting from chronic environmental exposure to chlorophenols can only be made for 2,4,6-trichlorophenol (2,4,6-TCP). The limited availability of toxicological data for 2-chlorophenol (2-CP) and 2,4-dichlorophenol (2,4-DCP) prevents an equivalent analysis for these compounds. Lifetime feeding of male mice with 2,4,6-trichlorophenol at ~600 mg/kg/day (5,000 ppm in diet) resulted in an increased incidence of hepatocellular carcinoma or adenoma above controls. Based on the results of several extrapolations of the animal data to estimate human dose-response, the predicted excess lifetime risk to humans of developing cancer from exposure to 10 μg/day, 100 μg/day, or 1,000 μg/day of 2,4,6-trichlorophenol is 0.1 to 3×10^{-6}, 0.4 to 3×10^{-5}, and 2 to 3×10^{-4}, respectively. Daily exposure to 2,4,6-trichlorophenol through drinking water only was estimated to range from 0.4 μg/day as a typical exposure level to 60 μg/day as a maximum which would be associated with a per capita risk of 1×10^{-10} to 2×10^{-5}. Fisheaters were estimated to be exposed to a maximum of 155 μg/day with a per capita risk between 1×10^{-5} and 5×10^{-5}.

Humans are rarely exposed to concentrations of 2-chlorophenol and 2,4-dichlorophenol in environmental media that are high enough to cause adverse effects. This is based on a very limited data base regarding both exposure and toxicological effects levels. The lowest effects level for 2,4-dichlorophenol is 7,000 mg/day, estimated for long-term exposure through ingestion. The maximum exposure level for humans drinking contaminated water and ingesting beef kidneys is four orders of magnitude below the effects level. No long-term feeding studies are available for 2-chlorophenol. Exposure levels, however, are significantly below acute and subacute effects levels.

7.2.2 Effects and Exposure Levels for Chlorophenols

Table 7-1 summarizes the exposure estimates described previously in Chapter 5.0. It is apparent that fish consumption presents the greatest potential for exposure to chlorinated phenols; no information regarding actual levels of chlorophenols in fish were available. Beef kidney consumption may

TABLE 7-1. HUMAN EXPOSURE TO CHLORINATED PHENOLS THROUGH INGESTION
(μg/day)

	2-Chlorophenol	2,4-Dichlorophenol	2,4,6-Trichlorophenol	Comments
Drinking water	100	60	60	Maximum ambient concentration of 30 μg/l. Consumption of 2 l/day.
	0.4[a]	0.4	0.4[a]	Mean concentration reported in drinking water (of positive values). Consumption of 2 l/day.
Food				
Fish	137	26	95	Maximum of all mean major river basin concentrations reported in ambient water approximately 30 μg/l for 2,4-DCP and 2,4,6-TCP; 50 μg/l for 2-CP. Respective BCF of 130, 40.7, and 150. Fish consumption of 21 g/day.
	27	9	32	Mean of all major river basin concentrations approximately 10 μg/l. Same assumptions as above.
Beef kidney	-	280	-	Maximum concentration reported in beef kidney (560 μg/kg). Kidney consumption of 0.5 day.

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[a] No information was available on typical levels of these substances in drinking water. Concentrations were assumed to be equivalent to those reported for 2,4-dichlorophenol.

Source: Chapter 5.0.

also be a significant exposure route for 2,4-dichlorophenol; however, due to rapid metabolism and clearance of the substance in mammals, this estimate represents a worst case. Consumption of contaminated drinking water is the only known exposure route for humans.

Tables 7-2, 7-3, and 7-4 describe lowest reported effect levels and no-effect levels, if available, for 2-CP, 2,4-DCP, and 2,4,6-TCP, respectively.

It has been shown that ingested 2,4,6-TCP is carcinogenic in male rats and both sexes of mice. No chronic feeding studies are available for the other two chlorinated phenols considered here; however, they both have been shown to possess tumor-promoting activity when applied dermally to mice, probably a result of an irritant response and of no relevance to ingestion exposures. Chromatid deletions have been reported in bone marrow cells of mice given 130 mg/kg 2-chlorophenol every other day for one week; data on the mutagenic activity of the other two compounds are inadequate. There is also no information available on the effects of these 3 chlorinated phenols on reproduction. Lethal oral doses for 2-CP and 2,4,6-TCP are in the 100 mg/kg to 900 mg/kg range, while 2,4-DCP is somewhat less toxic. An acceptable daily intake level of 7 mg/day has been proposed for human consumption of 2,4-dichlorophenol by the U.S. EPA (1980a).

Section 7.2.3 discusses the risk of adverse human exposure to 2,4,6-trichlorophenol and Section 7.2.4 addresses the risks associated with exposure to 2-chlorophenol or 2,4-dichlorophenol.

7.2.3 Risk of Exposure to 2,4,6-Trichlorophenol

7.2.3.1 Carcinogenicity of 2,4,6-Trichlorophenol

In this section, the potential carcinogenic risk to humans due to 2,4,6-trichlorophenol ingestion is estimated. Ideally, this problem would be dealt with in two ways:

- Various extrapolation models would be applied to occupational vs. ambient human exposure data (from retrospective studies) in order to obtain an approximate dose-response relationship.

- These same models would be applied to data from controlled experiments on laboratory animals, and the animal dose-response relationship would be converted to an estimated human dose-response.

In the first approach, the overriding uncertainty is in the data themselves; usually the exposure levels, lengths of exposure, and even response rates (responses per number exposed) are "best estimates," and, furthermore, unknown factors (background effects, etc.) may bias the data. In the second approach, the data are usually more accurate, but the relationship between animal and human response rates must be

TABLE 7-2. ADVERSE EFFECTS OF 2-CHLOROPHENOL IN MAMMALS

Adverse Effect	Species	Lowest Reported Effect Level	No Apparent Effect Level
Carcinogenicity			
ingestion	---	No data available	---
promotion DMBA-induced tumors	Mouse	25 µl/mouse two times per week, 20% soln., 15 weeks	---
Chromatid deletions	Mouse	130 mg/kg every other day for one week (bone marrow cells)	---
Altered liver function/pathology	Rat	65 mg/kg every other day for 3 weeks	---
Teratogenesis	---	No data available	---
Oral LD_{50}	Mouse	670 mg/kg	---

Source: Section 5.1.

TABLE 7-3. ADVERSE EFFECTS OF 2,4-DICHLOROPHENOL IN MAMMALS

Adverse Effect	Species	Lowest Reported Effect Level	No Apparent Effect Level
Carcinogenicity			
ingestion	---	No data available	----
promotion DMBA-induced tumors	Mouse	25 μl/mouse two times per week 20% soln., 15 weeks	----
Liver abnormalities	Mouse	~230 mg/kg/day for 6 mo.	~100 mg/kg/day for 6 mo.
Teratogenesis	---	No data available	---
Oral LD_{50}	Mouse	1,600 mg/kg	---
No effect level	Humans	---	Acceptable Daily Intake (ADI)[a] is 7 mg/day.

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[a] As reported by U.S. EPA (1980a).

Source: Section 5.1.

TABLE 7-4. ADVERSE EFFECTS OF 2,4,6-TRICHLOROPHENOL IN MAMMALS

Adverse Effect	Species	Lowest Reported Effect Level	No Apparent Effect Level
Hepatocellular Carcinoma	Mouse	5,000 mg/kg diet for 2 years[a]	----
Lymphoma/ Leukemia	Rat	5,000 mg/kg diet for 2 years[b]	----
Reticulum-cell Sarcoma	Mouse	260 mg/kg for 18 months	----
Promotion DMBA-Induced Tumors	Mouse	----	25 µl/mouse 2 times per week, 20% soln., 15 weeks
Teratogenesis	----	No data available	----
Oral LDLo	Man	500 mg/kg	----

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[a] Approximately 600 mg/kg for humans assuming a 25-gram mouse eats 3 grams of feed daily.

[b] Approximately 250 mg/kg for humans assuming a 180-gram rat eats 9 grams of feed daily.

Source: Section 5.1.

questioned. At present there is no universally accepted solution to this problem. In short, in the former case relevant data are of questionable validity; in the latter case valid data are of questionable relevance. If it is possible to perform both analyses and the results corroborate each other, confidence is gained in these results. If, on the other hand, data are not available for one of the two analyses and some result is assumed to be better than no result, the analysis must be performed based upon the available data.

Further complicating the issue, at present, is that there is no basis for judging the relative merits of the various extrapolation models. It is impossible to say which, if any, of them is correct. However, the models applied here are believed to be conservative (i.e., tend to overestimate the true risk).

7.2.3.2 Discussion of Available Data

The available data concerning human and other mammalian effects were discussed in Section 5.1.2. For 2,4,6-trichlorophenol, the best quantitative carcinogenicity data currently available are from a National Cancer Institute study (NCI 1979) with male and female F344 rats and B6C3F1 mice. The data indicate increased incidence of lymphoma or leukemia in male rats and of hepatocellular carcinoma or adenoma in both sexes of mice fed 2,4,6-trichlorophenol in the diet. The dose-response data from the study are listed in Table 7-5.

To deal with the uncertainties inherent in extrapolation, three commonly used dose-response models have been applied to the data in the table to establish a range of potential human risk. The assessment of potential human risk based on these models is subject to a number of important qualifications and assumptions:

- In view of possible species differences in susceptibility, pharmacokinetics, and repair mechanisms, the carcinogenicity of 2,4,6-trichlorophenol to humans is far from certain.

- Assuming that the positive findings indeed provide a basis for extrapolation to humans, the estimation of equivalent human doses involves considerable uncertainty. Scaling factors may be based on a number of variables, including relative body weights, body surface areas, and life spans.

- The large difference between the typically high experimental doses and the actual human exposure levels introduces uncertainty into the extrapolation from animals to humans. Due to inadequate understanding of the mechanisms of carcinogenesis, there is no scientific basis for selecting among several alternate dose-response models, which yield differing results.

TABLE 7-5. CARCINOGENIC RESPONSE IN RATS AND MICE FED 2,4,6-TRICHLOROPHENOL IN THE DIET

	Concentration in Animals' Food (mg/kg)	Equivalent Human Dose[a] (mg/day)	Response	Percent	Percent Excess Over Controls
Male Rats[b]	10,000	5,400	29/50	58	38
	5,000	2,700	25/50	50	30
	0	0	4/20	20	-
Male Mice[c]	10,000	5,600	39/47	83	63
	5,000	2,800	32/49	65	45
	0	0	4/20	20	-
Female Mice[d]	10,428	5,840	24/48	50	45
	5,214	2,920	12/50	24	19
	0	0	1/20	5	-

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[a] $$\underset{\text{(mg/day)}}{\text{Human dose}} = \underset{\text{(mg/kg)}}{\text{Concentration in Food}} \times \text{Animal Food Intake (mg/day)} \times \left(\frac{\text{Human weight}}{\text{Animal weight}}\right)^{2/3} \times \left(\frac{\text{Exposure Duration}}{\text{Total Animal Lifetime}}\right) \times 10^{-6} \text{ per mg/kg}$$

[b] Exposure beginning at age 6 weeks; ending with sacrifice of rats after 106 weeks of exposure, 107 weeks for controls.

[c] Exposure beginning at age 6 weeks; ending with sacrifice of mice after 105 weeks of exposure.

[d] Exposure beginning at age 6 weeks; high dose group at 20,000 mg/kg (in diet) for 38 weeks followed by 5,000 mg/kg for 67 weeks, for time-weighted average of 10,428 mg/kg for 105 weeks, low dose group at 10,000 mg/kg for 38 weeks, 2,500 mg/kg for 67 weeks, average of 5,214 mg/kg for 105 weeks.

Source: NCI (1979).

7.2.3.3 Calculations of Human Equivalent Doses

Obtaining a quantitative human risk estimate based on animal data requires first determining the human dose equivalent to a given animal dose. The approach used has been recommended by the EPA (Arthur D. Little, Inc. 1980) and normalizes the dose rate according to body surface area. This approach is relatively conservative in that it results in a lower equivalent human dose than would be obtained from simple multiplication of animal dose rate (mg/kg/day) by human body weight. Whether the surface area or body weight ratio is the more appropriate normalization factor is still open to debate. Neither ratio is ultimately correct, however, since differing metabolisms and other factors are ignored in either case. Since for mice the weight ratio is roughly 14 times the surface area ratio and for rats the weight ratio is roughly 6 times the surface area ratio, the choice of a conversion method introduces an uncertainty of an order of magnitude at least.

The rats were exposed to 2,4,6-trichlorophenol in their diet beginning at age 6 weeks and concluding with sacrifice of the rats after 106 weeks of exposure (107 weeks for controls), for a total rat lifetime of 112 weeks (113 weeks for controls). Male mice were exposed beginning at age 6 weeks for 105 weeks, giving a total lifetime of 111 weeks. Female mice were exposed at age 6 weeks. Females in the high-dose group were exposed to 20,000 mg/kg in the diet for 38 weeks, followed by 5,000 mg/kg for 67 weeks, for a weighted average dose of 10,428 mg/kg for 105 weeks. Females in the low-dose group were exposed to 10,000 mg/kg in the diet for 38 weeks, followed by 2,500 mg/kg for 67 weeks, for a weighted average dose of 5,214 mg/kg for 105 weeks. Total lifetime for all females was 111 weeks.

From this information, assumed body weights of 70 kg, 0.3 kg, and 0.025 kg for humans, rats, and mice, respectively, and assumed daily intakes of 3 g/day for mice and 15 g/day for rats, a human equivalent daily dose were estimated using the following equation:

$$\begin{matrix}\text{Human}\\ \text{Dose}\\ \text{(mg/day)}\end{matrix} = \begin{matrix}\text{Concentration}\\ \text{in Food}\\ \text{(mg/kg)}\end{matrix} \times \begin{matrix}\text{Animal}\\ \text{Food Intake}\\ \text{(mg/day)}\end{matrix} \times 10^{-6}\ \begin{matrix}\text{per}\\ \text{mg/kg}\end{matrix} \left(\frac{\text{Human Weight}}{\text{Animal Weight}}\right)^{2/3} \times \left(\frac{\text{Exposure Duration}}{\text{Total Animal Lifetime}}\right)$$

From this, a concentration in food of 1 mg/kg for mice is calculated to be equivalent to a dose of roughly 0.56 mg/day for humans. Similarly, 1 mg/kg for rats is calculated to be equivalent to a dose of roughly 0.54 mg/day for humans.

7.2.3.4 Estimation of Human Risk

The three dose-response models used to extrapolate human risk were the linear "one-hit" model, the log-probit model, and the multistage model. The latter is actually a generalization of the one-hit model in which the hazard rate is taken to be a quadratic rather than a linear function of dose. All of these models are well described in the literature, and a thoretical discussion may be found in Arthur D. Little, Inc. (1980). The one-hit and multistage models assume that the probability of a carcinogenic response is described by

$$P\ (\text{response at dose } X) = 1 - e^{-h(x)},$$

where h(x) is the "hazard rate" function. The log-probit model assumes that human response varies with dose according to a log-normal distribution. Due to their differing assumptions, these dose-response models usually give widely differing results when effects data are extrapolated from relatively high doses to the low doses typical of environmental exposure.

Since carcinogenic response in male mice was significantly higher than that in female mice and rats at roughly the same exposure level (see Table 7-5), only the data relating to male mice were used for dose-response extrapolation.

For the linear one-hit model, the equation

$$P(x) = 1 - e^{-Bx},$$

where P(x) is the probability of response to dose x, is solved for the parameter B. It may be shown that

$$B_x = \frac{1}{x} \ln \left(\frac{1 - P(o)}{1 - P(x)} \right),$$

where P(o) is the average control group response and P(x) is the response of the test group subjected to dose x. It is assumed that the "true" B value is given by

$$B \cong \left(B_{x_1} \cdot B_{x_2} \cdots\cdots\cdots B_{x_n} \right)^{1/n},$$

the geometric mean of the B_{x_i} from experimental data. From the data obtained from the study on male mice, B is calculated to be approximately 3×10^{-4} per mg/day.

For the log-probit extrapolation, the "probit" intercept A results from the following equation:

$$P_e(x) = \phi\ (A + \log_{10}[x]),$$

where ϕ is the cumulative normal distribution function, and $P_e(x)$ is the excess probability of response, $P_e(x) = P(x) - P(o)$.

This equation makes the usual assumption that the log-probit dose-response curve has unit slope with respect to the log-dose. From tables of the standard normal distribution, A (the geometric mean of the individually determined A_i), is found to be approximately equal to -3.5. This value was used to determine the probability of a response at various concentrations according to the above equation.

The multistage model with a quadratic hazard rate function,

$$h(x) = ax^2 + bx + c,$$

was also fit to the data. For estimating the parameters a, b, and c, a maximum likelihood method was used, aided by a computer program that performed a heuristic search for the best fit. It was found that $a \cong 7 \times 10^{-10}$, $b \cong 3 \times 10^{-4}$, and $c \cong 2 \times 10^{-1}$. The probability of response attributable to dose x is then given by

$$P(x) = 1 - e^{-(ax^2 + bx)}.$$

Note that since the value of the parameter a is vastly less than the value of b, P(x) varies linearly with dose for all doses below 1,000 mg/day. In this case (mainly by coincidence), the multistage and linear one-hit predictions are roughly identical. Normally, the multistage model predicts lower risk than the linear model.

Table 7-6 summarizes the risk estimates obtained from these three models. No attempt was made to determine statistical confidence bounds for the results. The uncertainties inherent in choosing a dose-response model and in determining a human equivalent dose make suspect any further purely statistical analyses of the data.

The estimates in Table 7-6 represent probable upper bounds on the true risk, since both the dose-response models and the estimation of human equivalent dose are believed to be conservative. Note, however, that the gap between the estimates is large in the low-dose region, so there is substantial range of uncertainty concerning the actual carcinogenic effects of 2,4,6-trichlorophenol. This points to the general lack of understanding of the mechanisms of carcinogenicity.

EPA's Cancer Assessment Group (CAG) has not specified 2,4,6-trichlorophenol as a potential human carcinogen. The EPA Water Quality Standard Division, however, calculated the risk associated with human exposure to ambient levels of 2,4,6-trichlorophenol in water. The same NCI study described previously was used and the CAG linear model was implemented for the extrapolation of risk. Table 7-7 presents the criteria for protection of humans from exposure to 2,4,6-trichlorophenol concentrations in surface water and the associated risk levels. Since the supporting calculations were not presented in the criterion document for chlorinated phenols, it was not possibly to compare the results of the four models.

TABLE 7-6. ESTIMATED LIFETIME EXCESS PROBABILITY OF CANCER[a] TO HUMANS DUE TO INGESTION OF 2,4,6-TRICHLOROPHENOL AT VARIOUS EXPOSURE LEVELS BASED ON THREE EXTRAPOLATION MODELS

Extrapolation Model	Exposure Level (mg/day):	Estimated Lifetime Excess Probability of Cancer at Indicated Exposure Levels					
		0.01	0.1	1	10	100	1,000
Linear Model		3×10^{-6}	3×10^{-5}	3×10^{-4}	3×10^{-3}	3×10^{-2}	3×10^{-1}
Log-Probit Model		$<1 \times 10^{-7}$	4×10^{-6}	2×10^{-4}	6×10^{-3}	7×10^{-2}	3×10^{-1}
Multistage Model		3×10^{-6}	3×10^{-5}	3×10^{-4}	3×10^{-3}	3×10^{-2}	3×10^{-1}

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[a] The lifetime excess probability of Cancer represents the increase in probability of cancer over the normal background incidence, assuming that an individual is continuously exposed to 2,4,6-trichlorophenol at the indicated daily intake over their lifetime. There is considerable variation in the estimated risk due to uncertainty introduced by the use of laboratory rodent data, by the conversion to equivalent human dosage, and by the application of hypothetical dose-response curves. In view of several conservative assumptions that were utilized, it is likely that these predictions overestimate the actual risk to humans.

TABLE 7-7. U.S. EPA INTERIM TARGET RISK LEVELS AND CORRESPONDING WATER QUALITY CRITERIA FOR 2,4,6-TRICHLOROPHENOL--PROTECTION OF HUMAN HEALTH

Exposure Assumptions (per day)	Risk Levels and Corresponding Criteria (µg/l)		
	10^{-7}	10^{-6}	10^{-5}
2 liters of drinking water and consumption of 6.5 grams fish and shellfish	0.12	1.2	12
Consumption of fish and shellfish only.	0.36	3.6	36

Source: U.S. EPA (1980b), p. C-75.

7.2.3.5 Conclusions

Daily exposure through drinking water to 2,4,6-trichlorophenol was estimated to be 60 μg/day for a maximum exposure with an average level around 0.4 μg/day (see Table 7-1). Fish-eaters are estimated to be exposed to a maximum of 155 μg/day and an average level of 32 μg/day assuming maximum and average drinking water exposure concurrently. The only known exposure routes for the compound are through ingestion of drinking water and contaminated fish. The average exposure through drinking water is based on the mean concentration in drinking water of 2,4-DCP. Daily exposure through contaminated fish are based on fish accumulating 2,4,6-TCP present in the environment at 30 μg/l and probably results in an overestimation.

Table 7-8 presents estimates of carcinogenic risk for various water borne routes of exposure to 2,4,6-trichlorophenol. For all maximum exposures, the risk factor is on the order of 10^{-5} to 10^{-6}. These calculations are based on uncertain exposure data. The probability of occurrence of these or higher concentrations of 2,4,6-trichlorophenol in fish and drinking water is unknown. The concentrations used in the calculation are either extrapolations from 2,4-dichlorophenol or based on physical and chemical properties. Additionally, there is no information on the industrial discharge of 2,4,6-trichlorophenol to surface water during its production; thus the likelihood of the compound entering drinking water is not known.

Since 2,4,6-trichlorophenol is sometimes used directly in pesticide applications (to a greater extent than the other two chlorophenols) there is a potential for exposure of humans during this use. The associated exposure levels are unknown due to an absence of data on application rates, frequency of use, and other important factors. There is a possibility that exposure levels may be higher than those presented in Table 7-1 and that, consequently, the associated potential for risk may be greater.

According to the EPA's Water Quality Criterion Document for chlorinated phenols (U.S. EPA 1980b), the maximum allowable concentration of 2,4,6-trichlorophenol in water to keep lifetime cancer risk below 10^{-5} is 12 μg/l, or about 0.02 mg/day, assuming a daily water consumption of 2 l/day for humans. (Note that the 12 μg/l figure is based on assumptions about indirect as well as direct exposure, particularly on average ingestion by humans of fish inhabiting waters at this concentration and on the concentrations in fish arising from this concentration in the water.) The four dose-response models predict an upper bound for risk between roughly 10^{-7} and 3×10^{-5} for a dose of 0.02 mg/day.

TABLE 7-8. ESTIMATES OF CARCINOGENIC RISK FOR VARIOUS WATER-BORNE ROUTES OF EXPOSURE TO 2,4,6-TRICHLOROPHENOL

	Estimated Lifetime Excess Probability of Cancer[a]			
	Drinking Water Only		Fish-Eaters	
Model	average (0.4 μg/day)	maximum (60 μg/day)	average 32 μg/day)	maximum (155 μg/day)
Linear and multistage	1×10^{-7}	2×10^{-5}	9×10^{-6}	5×10^{-5}
Log-probit	$<1 \times 10^{-10}$	1×10^{-6}	3×10^{-7}	1×10^{-5}

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[a] A range of probability is given, based on several different dose-response extrapolation models. The lifetime excess probability of cancer represents the increase in probability of cancer over the normal background incidence, assuming that an individual is continuously exposed to 2,4,6-trichlorophenol at the indicated daily intake over their lifetime. There is considerable variation in the estimated risk due to uncertainty introduced by the use of laboratory rodent data, by the conversion to equivalent human dosage, and by the application of hypothetical dose-response curves. In view of several conservative assumptions that were utilized it is likely that these predictions overestimate the actual risk to humans.

The discrepancies between the EPA risk predictions and those derived here arise from differing assumptions about the data and about human equivalent dose, from mathematical differences in the dose-response models, and from the fact that the model EPA implemented uses a 95% upper confidence bound in calculating its predicted risk.

7.2.4 Margins of Safety for Exposure to 2-Chlorophenol and 2,4-Dichlorophenol

The exposure data presented in Table 7-1 can be compared with the effects data in Tables 7-2 and 7-3 to determine the margins of safety associated with human exposure to 2-chlorophenol and 2,4-dichlorophenol concentrations in environmental media. These comparisons are presented in Table 7-9.

The margins of safety (effects level/exposure level) for exposure to 2-chlorophenol are equal to 2×10^4 for the maximum exposure through drinking water and fish consumption and approximately 1×10^7 for a more typical exposure through drinking water only. The margins of safety for both maximum and typical exposure to 2,4-dichlorophenol are greater than 2×10^4 and 2×10^7, respectively.

It must be emphasized that these calculations of safety margins are based on very limited effects and exposure data. In the case of 2-chlorophenol, the effects level used in the calculation is from a three week subacute study in rodents. Chronic studies, which are not available at this time, are likely to result in the determination of lower effects levels which would be reflected in a decreased margin of safety. Similarly, although the effects study for 2,4-dichlorophenol is a longer-term study, it was not possible to evaluate the reliability of the results nor were any similar studies available to corroborate the conclusions. Therefore additional chronic data may also reduce the margin of safety.

There is also a large degree of uncertainty associated with the exposure data. Monitoring data were extremely limited, with actual concentrations available only for 2,4-dichlorophenol in drinking water, 2-chlorophenol in fish tissue, and 2,4-dichlorophenol in beef kidney. All other concentrations are estimates based on extrapolations from similar chemicals or theoretically based on physical and chemical properties. The frequency distribution of chlorophenol concentrations in exposure media, therefore, is unknown due to data inadequacies. In addition, it was not possible to estimate exposure to the compounds through other routes of exposure (inhalation, dermal absorption) due to lack of data.

TABLE 7-9. MARGINS OF SAFETY FOR HUMAN EXPOSURE TO 2-CHLOROPHENOL AND 2,4-DICHLOROPHENOL

	Exposure (μg/kg/day)[a]		Lowest Effects Level (μg/kg/day)	Margin of Safety[b]	
	Typical	Maximum		Typical	Maximum
2-Chlorophenol			Altered liver function: 65,000[c] (orally every other day for 3 weeks)		
• drinking water	0.006	1.4		1×10^7	5×10^4
• fish consumption	0.4	2.0		2×10^5	3×10^4
TOTAL	0.4	3.4		2×10^5	2×10^4
2,4-Dichlorophenol			6 mo. no effects level ≅ 100,000[d]		
• drinking water	0.006	0.9		2×10^7	1×10^5
• fish consumption	0.1	0.4		1×10^6	3×10^5
• kidney consumption	-	4.0		-	3×10^4
TOTAL	0.1	5.3		1×10^6	2×10^4

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[a] Calculated for a 70-kg human.

[b] $\frac{\text{Effects level}}{\text{Exposure level}}$.

[c] Results of a single study (Chung 1978) with rats. The future availability of chronic studies may substantially lower the lowest effects level.

[d] Results of a single study (Kobayashi et al. 1972) on mice. The future availability of chronic studies may substantially lower the lowest effects level.

Taking into account the large amount of uncertainty inherent in the calculated margins of safety, it can be concluded that humans are rarely exposed through ingestion to concentrations of 2-chlorophenol and 2,4-dichlorophenol in environmental media that are high enough to cause adverse effects. Exposure through dermal absorption is not expected to be significant due to the low concentrations of chlorophenol in ambient and drinking water. Human exposure through inhalation was not possible to evaluate due to a lack of data. The highest inhalation-related exposure would probably be through herbicide use, through occupational exposure, and in subpopulations living in the vicinity of chemical production plants. Atmospheric releases of chlorophenols are minimal on a national level, so ambient air concentrations to which the majority of the U.S. population are exposed are likely to be negligible. These speculations require monitoring data for validation.

7.2.5 Recommendations

There are numerous areas in which additional work could strengthen this exposure and risk assessment. While it is obvious that more monitoring and toxicological data are needed, other specific areas in which further work is needed are:

- Investigations into the formation of chlorinated phenols in soil and food items resulting from the use of compounds such as 2,4-D and 2,4,6-T.

- More detailed descriptions of the uses of 2-CP, 2,4-DCP, and 2,4,6-TCP and products containing them. Although the compounds are largely used as intermediates, significant exposure routes may result from other, currently undefined uses of these compounds.

7.3 AQUATIC BIOTA

The monitoring data provided by STORET (U.S. EPA 1979) were insufficient to allow estimation of chlorinated phenol exposure levels to aquatic organisms on a national scale. Observations in major river basins consisted of remarked data, all below 100 μg/1; a large majority of the observations in the United States (excluding the Pacific Northwest) were between 1.1 μg/1 and 10.0 μg/1. In the Pacific Northwest, where the greatest number of samples was taken, 71% of the measurements for the three chlorinated phenols fell between 10.1 μg/1 and 100.0 μg/1. This may indicate that less sensitive detection techniques were used in the analysis of samples from this basin rather than that there were higher actual concentrations of chlorophenols. Monitoring for these compounds should be conducted more frequently in all basins if an accurate nationwide assessment of risk is to be made. The effects of such aqueous parameters as pH, hardness, and temperature on the toxicity of chlorinated phenols have not been studied adequately, therefore, their significance with regard to a geographical analysis of risk is uncertain.

According to the toxicity data surveyed in the previous chapter, the lowest level of any chlorinated phenol which produced toxic effects in laboratory studies was 320 μg/l for 2,4,6-TCP (an LC_{50} for bluegill). None of the environmental concentrations reported in STORET (1979-1979) exceeded 100 μg/l for any of the three compounds, which suggests that aquatic biota are probably not at serious risk with respect to long-term exposure to chlorinated phenols.

There is a possibility that chronic sublethal effects could appear in aquatic organisms at concentrations well below 320 μg/l. Very few species, and perhaps not the most susceptible ones, have been bioassayed for their reactions to the chlorinated phenols, so the available data may not accurately reflect the potential sensitivity of aquatic species or ecosystems. There are indications that fish can fairly rapidly metabolize and excrete low levels of chlorophenols, so the potential for long-term sublethal effects may be reduced through this mechanism.

Several fish kills have been attributed to chlorophenols released from wood-preserving and chemical production plants and from a cooling tower discharge. The presence of other substances in the effluent especially from the wood-preserving plant, may have contributed to the adverse effects on the aquatic communities exposed. However, the incidents suggest that there is a risk for aquatic species to be acutely exposed to adverse levels of chlorophenols. Chemical production plants, wood-preserving facilities, and textile plants are expected to be the most likely to spill chlorophenols at high enough concentrations to result in deleterious effects on aquatic ecosystems.

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APPENDIX A: PRODUCTION AND EMISSION ESTIMATES

1. PRODUCTION ESTIMATES

There are thirteen isomers of chlorophenols commercially available. Production data on these compounds (except for 2,4-chlorophenol and pentachlorophenol) are proprietary in order to protect each producer's market position. Some producers only produce one of the isomers, probably in very small quantities. Production estimates for the three isomers addressed in this report are based on previously reported estimates, the known production numbers on two of the isomers, and the estimated amount of phenol used to manufacture these compounds. The year 1977 has been chosen as the basis year.

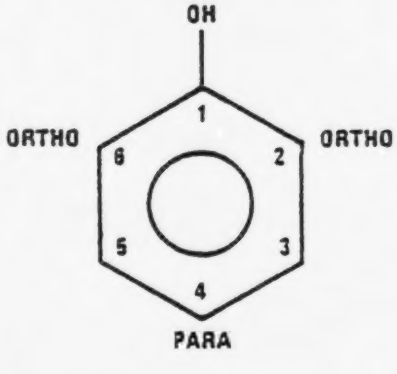
AMOUNT OF PHENOL USED FOR CHLOROPHENOL PRODUCTION

Using data published by Monsanto Company, Versar, Inc. (1980) estimated the amount of phenol used in chlorophenol manufacture as follows:

Product	Amount of Phenol (kkg)
2,4-dichlorophenoxyacetic acid[1]	10,366
Pentachlorophenol	5,183
All other chlorophenols	15,550
	31,099

All of the isomers can be produced via the direct chlorination of phenol or the hydrolysis of the appropriate chlorobenzene.

The hydroxyl group in phenol is an extremely powerful ortho-para director. Halogenation of phenol results almost exclusively in substitution at the 2,4, or 6 positions on the aromatic ring (Morrison and Boyd 1973).



If phenol is used as the raw material for production of chlorophenols, the phenol chemistry dictates the following product distribution upon successive substitution:

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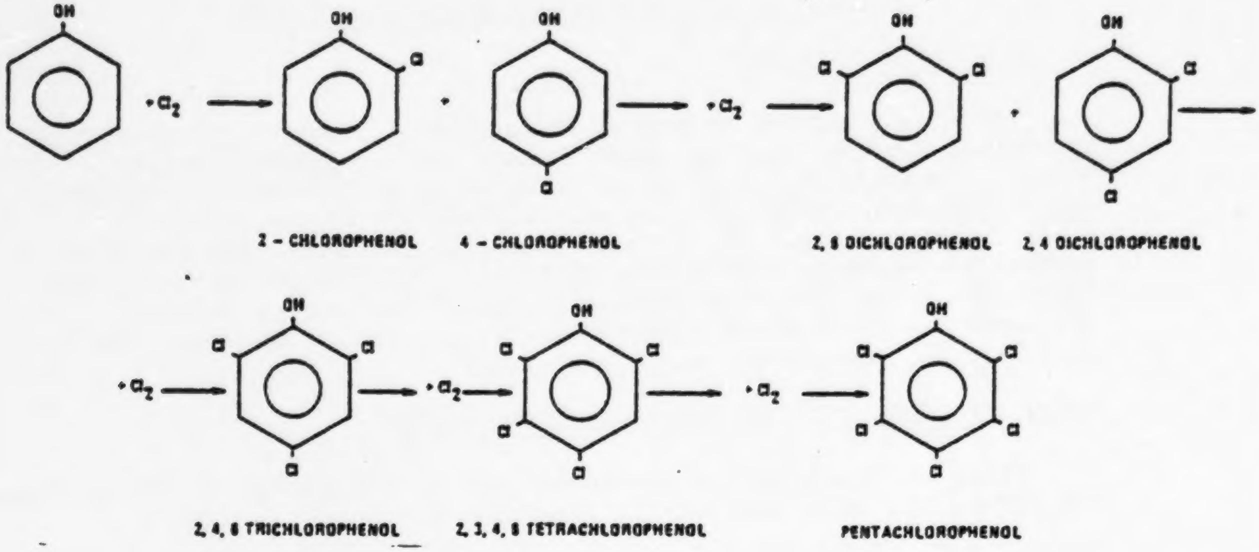
[1] a derivative of 2,4-dichlorophenol.


+Cl2
2 - CHLOROPHENOL
4 - CHLOROPHENOL
+Cl2
2,6 DICHLOROPHENOL
2,4 DICHLOROPHENOL
+Cl2
2,4,6 TRICHLOROPHENOL
+Cl2
2,3,4,6 TETRACHLOROPHENOL
+Cl2
PENTACHLOROPHENOL

Therefore, it is likely that the remaining isomers are produced via the hydrolysis of the appropriate chlorobenzene. Although any of the isomers above can also be made via the hydrolysis of a chlorobenzene, it is not likely to be the preferred route since hydrolysis can give rise to the unwanted formation of chlorinated dibenzo-p-dioxins.

ESTIMATED PRODUCTION OF 2,4-DICHLOROPHENOL

Two methods were used to estimate the production in 1977 of 2,4-dichlorophenol.

Method 1:

Year	Production (kkg)	Sales (kkg)
1978	12,009[a]	3,593[a]
1977	-	4,031[b]

$$\text{1977 Production} = (\text{1978 Production})\left(\frac{\text{1977 sales}}{\text{1978 sales}}\right)$$

$$= (12{,}009\ \text{kkg})\left(\frac{4{,}031\ \text{kkg}}{3{,}593\ \text{kkg}}\right)$$

$$= 13{,}472\ \text{kkg}$$

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[a] USITC (1979).

[b] USITC (1978).

Method 2:

The compound 2,4-dichlorophenol is the precursor for the production of 2,4-dichlorophenoxyacetic acid (2,4-D). Versar, Inc. (1980) estimates that about 10,366 kkg of phenol were used for the production of 2,4-D via the 2,4-DCP route. The yield of the reacion is about 80% (Morrison and Boyd 1973).

$$\text{1977 Production} = (\text{Amount of phenol used for 2,4-D})\left(\frac{\text{molecular wt of 2,4-DCP}}{\text{molecular wt of phenol}}\right)(\text{yield})$$

$$= (10{,}366\ \text{kkg})\left(\frac{163}{93}\right)(0.80)$$

$$= 14{,}534\ \text{kkg}$$

The second method has assumed that virtually all of the 2,4-dichlorophenol production is via the chlorination of phenol. This is a reasonable assumption because two producers (Dow and Monsanto) produce ortho and para monosubstituted chlorophenol and Dow produces 2,4,6 and pentachlorophenols, which is consistent with phenol chemistry. According to JRB Associates (1980), the other two producers of 2,4-dichlorophenol did not produce the compound in 1977 and one of these producers makes the 2,4,5 trisubstituted product, which would be consistent with the hydrolysis route. Additionally, Tracor-Jitco (1978) estimated the annual production of 2,4-dichlorophenol to be about 14,000 kkg. These three estimates are independent of each other and within 5% of each other. Therefore, the estimated production in 1977 of 2,4-dichlorophenols is 14,000 kkg.

ESTIMATED PRODUCTION OF OTHER CHLOROPHENOLS

The estimated production of 2 and 4 monochlorophenols, 2,4,6-trichlorophenol, 2,3,4,6-tetrachlorophenol, and pentachlorophenol is not as well defined as is that for 2,4-dichlorophenols because the lower chlorophenols are used to produce the higher chlorophenols.

Production of pentachlorophenol in 1977 was 20,345 kkg (USITC 1978). Reportedly, pentachlorophenol is only made by the direct chlorination of phenol at about an 85% yield on a phenol basis (Morrison and Boyd 1973).

$$\text{Phenol consumption} = \frac{(\text{pentachlorophenol production})\left(\dfrac{\text{molecular wt of phenol}}{\text{molecular wt of pentachlorophenol}}\right)}{(\text{yield})}$$

$$= (20{,}345\ \text{kkg})\left(\frac{93}{260}\right)\Big/(0.85)$$

$$= 6{,}185\ \text{kkg}$$

Since only 5,183 kkg of phenol were used for pentachlorophenol production, however, an additional 3,123 kkg of phenol equivalents of lower chlorophenols were consumed to account for the pentachlorophenol production. This leaves about 12,427 kkg of phenol equivalents for the production of the isomers via the chlorination of phenol.

JRB Associates (1980) estimates that about 2,000 kkg of the ortho monochlorophenol and 1,300 kkg of the para monochlorophenol are produced via the hydrolysis of dichlorobenzene. They further estimate that about 1% of the ortho product and 13% of the para product are isolated for consumptive use, while the remainder is used to produce higher chlorophenols. Assuming that the phenol equivalents unaccounted for are used for the production of these two isomers at 80% yield shows for the production of monochlorophenol via direct chlorination:

$$\text{Amount} = (\text{Amount of phenol})\left(\frac{\text{molecular wt of chlorophenol}}{\text{molecular wt of phenol}}\right)(\text{yield})$$

$$= (12{,}427 \text{ kkg}) \left(\frac{128}{93}\right) (0.80)$$

$$= 13{,}683 \text{ kkg}$$

Because of the non-specificity of the reaction, the ortho-to-para ratio is about 45/55, respectively (Morrison and Boyd 1973). Therefore:

ortho product = (13,683 kkg) (0.45) = 6,157 kkg
para product = (13,683 kkg) (0.55) = 7,526 kkg
Total ortho production = 6,157 kkg + 2,000 kkg = 8,157 kkg ≈ 8,150 kkg
Total para production = 7,526 kkg + 1,300 kkg = 8,826 kkg

The amount of monochlorophenol used to produce the 2,4,6- and 2,3,4, 6-chlorophenols via direct chlorination is:

$$\text{Amount} = (8{,}157 \text{ kkg})\ (1-0.01) + (8{,}826 \text{ kkg})\ (1-0.13)$$

$$= 15{,}754 \text{ kkg}$$

Assuming an 80% yield upon chlorination of the monochlorophenol to the tri and tetra substituted products, the amount of phenol equivalents contained in these two products is:

$$\text{Phenol equivalents} = (\text{Amount of monochlorophenol} \left(\frac{\text{molecular wt of phenol}}{\text{molecular wt of chlorophenol}}\right) (0.80)$$

$$= 9{,}157 \text{ kkg}$$

Assuming only 2,4,6 is produced:

$$\text{Amount produced} = (9{,}157 \text{ kkg}) \left(\frac{163}{93}\right) = 16{,}048 \text{ kkg max.}$$

Assuming only 2,3,4,6 is produced:

$$\text{Amount produced} = (9{,}157 \text{ kkg}) \left(\frac{198}{93}\right) = 19{,}495 \text{ kkg max.}$$

It is likely that both are produced and therefore that the production of each is less than the maximum quantity derived above. Production quantities of these two compounds are interdependent.

2. EMISSION ESTIMATES[1]

2-Chlorophenol

Emission factors from production:

Water: 2.1×10^{-2} kkg/kkg product
Air: 5% of aquatic discharges
Land: negligible

$$\text{Water discharges} = (2.1 \times 10^{-2} \text{ kkg/kkg})\ (8{,}150 \text{ kkg}) \approx 170 \text{ kkg}$$

$$\text{Air discharges} = (0.5)\ (170 \text{ kkg}) \approx 8.6 \text{ kkg}$$

Emission factors for uses:

Phenolic resin production = 0.005 of production
Solvent usage = 0.005 of production
Total emissions from use = (2) (0.005) (8,150)

2-4 Dichlorophenol

Emission factors for production:

Water: 2.1×10^{-2} kkg/kkg product
Air: 1×10^{-3} kkg/kkg product
Land: negligible

$$\text{Air emissions} = (14{,}000 \text{ kkg})\ (1 \times 10^{-3} \text{ kkg/kkg}) = 14 \text{ kkg}$$

$$\text{Aquatic discharges} = (14{,}000 \text{ kkg})\ (2.1 \times 10^{-2} \text{ kkg/kkg}) \approx 294 \text{ kkg}$$

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[1] Data extracted from JRB Associates (1980).

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